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ENG460 Engineering Thesis

The A1 Wind Farm:

An investigation into the voltage control, network support capability and stability of the A1 distribution network.

A report submitted to the School of Engineering and Energy, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering

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westernpower

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Abstract

The wind energy generation investigated by this thesis is the A1 Wind Farm. This thesis aims to investigate the voltage control capabilities of the wind farm and how the wind farm is able to provide network voltage support through the generation and absorption of reactive power. The thesis also aims to investigate how the voltage control capabilities and reactive power support affect the voltage stability of the network. These aims will be referred to as voltage control, network support capability and stability of the network.

The A1 Wind Farm consists of twelve 1800kW wind turbine generators, manufactured by ENERCON. These wind turbines are variable speed, pitch controlled, using synchronous generators with a full scale power converter which is coupled to the SWIS. Specifically, the role of the A1 Wind Farms power converter and its control has been investigated. The power converter has proven to be vital to the voltage control, network support capability and stability of the A1 Distribution Network. The thesis analyses the A1 Wind Farm (AWF) by using PowerFactory Version 14. This is used to construct a model that represents the A1 distribution network and A1 Wind Farm. These simulations are conducted using steady state and transient conditions.

The findings of the steady state investigation was that operating the AWF at a limited active power output of 15MW and a power factor of 0.95 leading would result in the least impact on the voltage of the Western Power customers. By using limited active power and power factor control (PQ) it resulted in the least amount of tap changers with a changing load and AWF generation. In turn this resulted in reduced-

maintenance of the tap changer and a decrease in voltage fluctuations at the 22kV busbar of the A1 zone substation.

The power factor of 0.95 leading (absorbing reactive power) also compensated for the voltage rise in the capacitive transmission and distribution network during low load conditions. When using a fixed PQ control for the "constructed" AWF model, it acts like a negative load model. Thus, all the synchronous generator reactive power capabilities had no influence on the voltage at steady state. This is because the reactive power flow of the generator is decoupled by the power converter.

From the transient investigation, it was concluded that the AWF must have under voltage ride through (UVRT) capabilities. UVRT is important to the voltage control, network support capability and stability of the A1 network, because this specific capability allows the AWF to remain online and to generate reactive power output even if its voltage is under the required limits. If the AWF was required to disconnect after a fault then the voltage levels and stability would be worse than if it remained connected. Also, using the same PQ control used for the steady state investigation for transient analysis caused problematic results. This is because PQ control makes the power converter absorb reactive power after the fault has been cleared when in fact the power converter control should support the voltage by generating reactive power.

Therefore, by reverting to voltage control from constant PQ control, the AWF has also reverted from absorbing reactive power to generating reactive power. In doing this the AWF has provided reactive power support following the fault. Thus, the AWF should utilise V control instead of PQ control under transient conditions and this voltage control and UVRT should be triggered by the under voltage of 0.8 per unit.

In conclusion, under transient conditions, the under voltage ride through capabilities of the A1 Wind Farm were essential to the voltage control, network support capability and stability of the A1 distribution network.

Confidentiality notice

The wind farm within this thesis has been referred to as the A1 Wind Farm due to confidentiality agreements between the wind farms owners and Western Power. To protect all parties from litigation issues, the intention of the author is not to refer to any particular wind farm but to a general hypothetical model. This will be referred to from now on as the A1 Wind Farm.

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Table of Contents

Abstract i
Confidentiality notice iv
Acknowledgments v
Table of Contents vi
List of Figures viii
List of Tables ix
List of Acronyms x
1 Introduction 1
1.1 Thesis structure and aims 3
1.2 Thesis scope outline 5
2 Background 6
2.1 South West Interconnected System 7
2.2 SWIS structure 8
2.3 SWIS voltage limits 9
2.4 SWIS stability 9
2.5 Disturbances 10
2.6 Steady state stability 11
2.7 Transient stability 11
2.8 Voltage stability 12
2.9 Wind generations impact on stability 14
3 The A1 distribution structure and AWF 16
3.1 A1 distribution structure 16
3.2 Substation loads 18
3.3 A1 Wind Farm feeders 20
3.4 A1 Wind Farm 21
3.5 ENERCON wind turbines 22
3.6 Power converter coupled generator construction 22
3.7 The power converter 24
3.7.1 Power converter operation performance 24
3.7.2 Control of the power converter 26
3.7.3 ENERCON fault ride through capabilities 28
3.7.4 ENERCON under voltage ride through (UVRT) 29
3.7.5 A1 Wind Farm under voltage ride through (UVRT) 30

4 Network modelling approach ... 31
4.1 Data collection ... 31
4.2 PowerFactory construction ... 33
4.3 Models ... 34
4.3.1 External grid model ... 34
4.3.2 Terminal model ... 35
4.3.3 Transformer model ... 35
4.3.4 General load model ... 37
4.3.5 Induction machine model ... 37
4.3.6 Line model ... 38
4.3.7 Synchronous generator model ... 39
4.3.8 Rectifier model ... 41
4.3.9 Inverter model ... 41
5 Testing the PowerFactory simulation ... 44
5.1 Steady state investigations ... 44
5.1.1 Determine maximum active power output from the A1 Wind Farm. ... 45
5.1.2 Preferred A1 Wind Farm power factor ... 47
5.1.3 Scenario 1 Analysis (A1 Wind Farm output = 1MW, Peak load = 40MW) ... 52
5.1.4 Scenario 2 Analysis (A1 Wind Farm output = 15MW, low load = 10MW) ... 52
5.1.5 Optimum power factor at steady state ... 54
5.1.6 A1 Wind Farm model steady state behaviour ... 56
5.1.7 Conclusions of steady state investigation ... 58
5.2 Transient investigations ... 59
5.3 Scenario 3, analysis using PQ control (22kV busbar fault) ... 61
5.3.1 Voltage per unit analysis ... 62
5.3.2 Reactive power analysis ... 63
5.4 Scenario 3, analysis using voltage control (22kV busbar fault) ... 67
5.4.1 Voltage per unit and reactive power analysis (voltage control) ... 68
5.4.2 Conclusions from the transient investigation (voltage control) ... 70
6.0 Scope for future work ... 72
6.1 Expansion of the A1 Wind Farm (AWF) ... 72
6.2 Optimising the active power output ... 72
6.3 Further investigation of voltage instability ... 73
7 Conclusion ... 74
8 References ... 76
Appendices ... 78

List of Figures

Figure 1: South West Interconnected System [1] 7
Figure 2: Diagram of SWIS structure [1] 8
Figure 3: A1 zone substation layout [1] 17
Figure 4: A1 peak load forecast 1996 to 2027 [1] 18
Figure 5: Direct-drive power converter generator [9] 23
Figure 6: General capability chart of ENERON wind turbines with FACTS Capabilities: 25
Figure 7: Structure of ENERCON farm Control Unit for wind farm voltage control [11] 27
Figure 8: External Grid model [13] 34
Figure 9: Delta – Delta transformer model [13] 36
Figure 10: Delta – Wye neutral transformer model [13] 36
Figure 11: Balanced three phase PQ load model [13] 37
Figure 12: Three phase induction machine model [13] 37
Figure 13: HV Cable models 38
Figure 14: Synchronous generator model [13] 39
Figure 15: Rectifier model [13] 41
Figure 16: Pulse width modulator inverter model [13] 41
Figure 17: A1 distribution network and the A1 Wind Farm model created within PowerFactory 43
Figure 18: Inverter theory in relation to power factor [adapted from 16] 48
Figure 19: A1 Wind Farm connection busbar, 22kV busbar fault simulation 62
Figure 20: A1 Wind Farm connection busbar, 22kV busbar fault simulation 66
Figure 21: A1 Wind Farm connection busbar, 22kV busbar fault simulation (voltage control) 68

List of Tables

Table 1: Steady state optimum power factor test 51

List of Acronyms

ADN – A1 Distribution Network

AWF – A1 Wind Farm

DFIS – Distributed Facilities Information System

DQ - Direct and Quadrature Axis

FACTS – Flexible Alternating Current Transmission System

FCU – Farm Control Unit

FRT – Fault Ride Through

HV – High Voltage

IGBT – Insulated Gate Bipolar Transistor

kV – Kilovolts

LV – Low Voltage

MVAr – Mega Volt Amperes Reactive

MW – Mega Watt

NOCC - Western Power East Perth Control Centre

PF – Power Factor

PFY – PowerFactory

PQ – Active and Reactive Power

PU – Per Unit

R – Resistance

SCADA - Supervisory Control and Data Acquisition

SG – Synchronous Generator

STATCOM – Static Synchronous Compensator

SWIS – South West Interconnected System

UVRT – Under Voltage Ride Through

V – Voltage

X – Reactance

Z – Impedance

1 Introduction

Although wind energy generation has the largest proportion of renewable energy generation in Western Australia, little research has been conducted into its voltage control and the impact of this control on the South West Interconnected System (SWIS). Therefore, the purpose of this research is to investigate the voltage control capabilities of a wind farm and how the wind farm is able to provide network voltage support through the generation and absorption of reactive power.

The wind energy generator that is investigated by this thesis is the A1 Wind Farm. This is because this thesis aims to investigate the voltage control and network support capability of power converter coupled wind generation within the SWIS. Thus, the A1 Wind Farm was chosen because it uses power converter coupled technology and plays a vital role in voltage control, network support and stability of the A1 Distribution Network within the SWIS.

Furthermore, the role of the A1 Wind Farms power converter and its control has been investigated. The power converter has proven to be vital to the voltage support, control and stability of the A1 Wind Farm (AWF).

In order to understand the power converters control, the background of the A1 Wind Farms turbine technology was investigated and understood. Once completed the thesis analyses the A1 Wind Farm by using PowerFactory Version 14 to construct a model that represents the A1 distribution network and the A1 Wind Farm.

This model is used to simulate different generation outputs and loads, while changing the power factor and the control of the A1 Wind Farm.

These simulations are conducted using steady state and transient investigations.

The steady state investigation uses two worst case scenarios. These scenarios are used to investigate the A1 Wind Farms impact on voltage fluctuations, at the 22kV busbar of the A1 zone substation.

The transient investigation uses one worst case scenario and transient condition. The transient condition is created by a short circuit fault at the 22kV busbar. This is to test the control, voltage support and voltage stability of the A1 Wind Farm under transient conditions and to validate or reject the findings of the steady state investigation.

1.1 Thesis structure and aims

The structure of the thesis is sectionalised in order to cover the aims of the thesis. Each section and its sub section will cover a different aim. The outline of the section structure and the aims are as follows:

Section	**Aim**
Section 2	Review the structure of the SWIS. Review the SWIS voltage limits. Define steady state, transient and voltage stability. Investigate and discuss the impact of wind generation on stability. Choose a distribution network for a case study (the A1 distribution network)
Section 3	Describe the A1 distribution network structure and zone substation loads. Investigate and discuss the A1 Wind Farm. Describe the ENERCON wind turbines and their use of synchronous generation with power converter coupled technology. Investigate and discuss ENERCON and the A1 Wind Farm fault ride through capabilities.

Section 4	Model and simulate the A1 distribution network and A1 Wind Farm. Describe how this model was constructed using Power Factory.
Section 5	Test the model using steady state and transient network conditions. Investigate and discuss the A1 Wind Farms control, behaviour and voltage stability that results from both steady state and transient conditions.
Section 6	Discuss the scope of future work that could be based upon this thesis.

1.2 Thesis scope outline

The scope of this thesis is limited to the A1 distribution network and how it is affected by the A1 Wind Farm and its control. The impact on the SWIS has been limited to a distribution network level. This is because there are many different factors that impact on the voltage of the SWIS and it is not the purpose of this thesis to analyse all of these factors.

However, the power system analysis of the A1 distribution network and the theories discussed in relation to power, voltage control and stability can still be applied to the SWIS. Although, the theories developed may have to be applied differently due to higher system voltages, generator technologies, network size and diversity.

For the steady state investigation, the scope of this thesis has been limited to two worst case scenarios. This is a conventional approach to power system analysis. This approach is replicated by Western Power. By analysing the worst case scenarios this thesis has determined the limits of the A1 Wind Farm.

The transient investigation has been limited to one worst case scenario. This scenario uses a three phase short circuit fault at the 22kV busbar of the A1 zone substation. In doing this, the behaviour of the AWF's voltage control and reactive support capabilities are specifically tested.

2 Background

Within the South West Interconnected System or SWIS, the connection of wind farms is a regular occurrence. The wind farm that is investigated within this thesis is the A1 Wind Farm. This wind farm affects the voltage stability of the A1 Network. This thesis conducts steady state and transient investigations to determine its voltage control, network support capability and stability of the network. Before this investigation can be performed, one must understand the structure of the SWIS and the A1 Distribution Network.

2.1 South West Interconnected System

The South West Interconnected System or SWIS is Western Australia's (WA) main power supply network. The SWIS is owned and operated by Western Power which is responsible to maintain and improve the network in order to provide electricity to 906,596 customer meters [1]. Figure 1 shows the extent of the SWIS network. Highlighted in blue, the SWIS extends north to Kalbarri, east to Kalgoorlie and south to Albany. It consists of over 775 000 power poles, 6957 km of transmission line and 115 000 km of distribution line. In order to supply power in a safe, efficient and reliable manner, its maintenance and structure is relentless and meticulous.

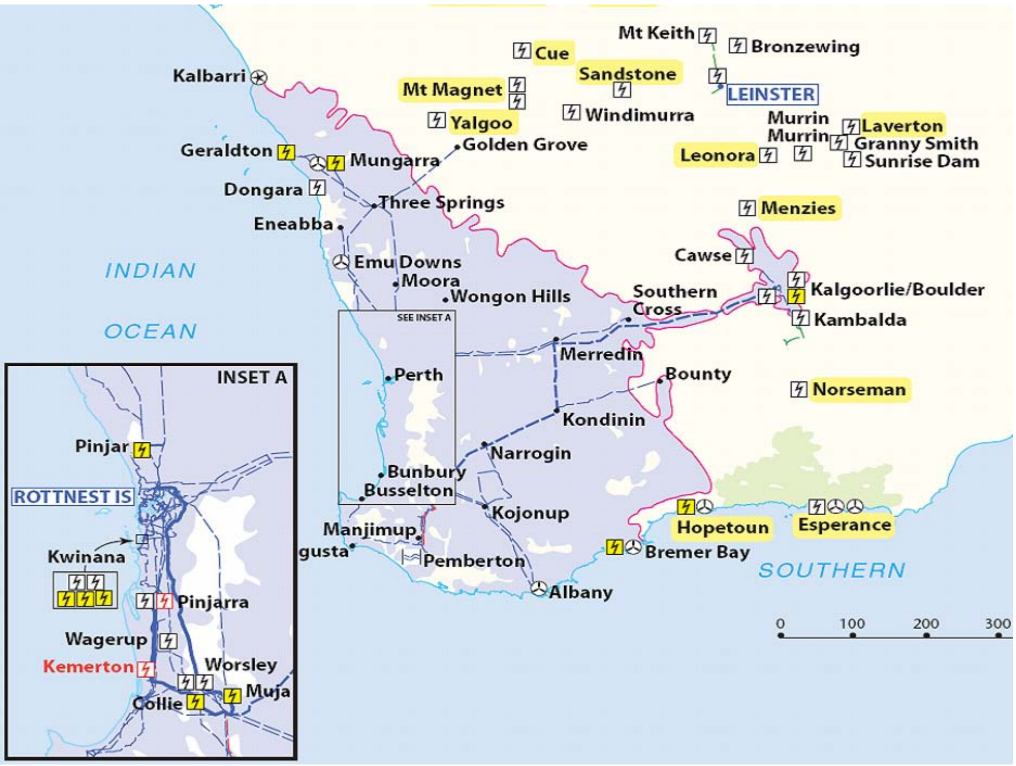

Figure 1: South West Interconnected System [1]

2.2 *SWIS structure*

The structure of SWIS is divided up into three sections, generation, transmission and distribution. Figure 2 shows the elements of generation, transmission and distribution.

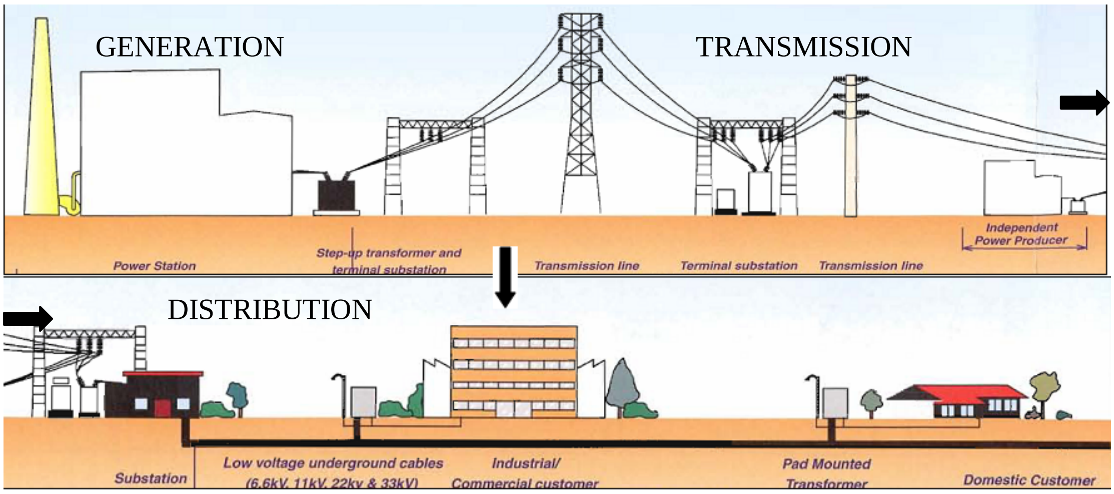

Figure 2: Diagram of SWIS structure [1]

Figure 2 shows that the power flows from the generation source to the transmission line, via a transformer, stepping up from typically 11 or 16 kV at the generator to 132 kV to 330kV. Power then flows to a terminal substation where it is regulated and retransmitted by several transmission feeders. At the substation (zone) various other independent power generators provide power into the transmission grid. The power then reaches the distribution zone substation where it is stepped down to 6.6, 11, 22 and 33 kV. Here the distribution network begins. Power is then reticulated to transformers to be stepped down again to 415 volts line to line and consumed by customers. Power generators also supply power into the distribution network, but these are at a much smaller scale than the generation within transmission networks. This is known as distributed generation (DG) as opposed to the centralised generation in transmission networks.

2.3 SWIS voltage limits

The voltage limits of the SWIS are specified by the Western Power Technical Rules [2]. Within distribution networks the high voltage limits are 0.9 to 1.1 pu, or plus or minus 10% [2].

If a generator remains outside these voltage limits for longer than a stipulated time then voltage instability can occur. However, for each wind generator the connection requirements are specifically negotiated with Western Power. This is because not all wind generators, such as the induction type, can provide full voltage support and may have to be disconnected during emergency conditions. These connection agreements between the wind farm owner and Western Power are confidential and are not available due to possible litigation issues. However, the approach of this thesis is to utilise the above voltage limits to determine voltage stability of the A1 Wind Farm.

In order to understand voltage stability, the stability of the SWIS is outlined. In doing this, the disturbances that affect the stability of the SWIS and their relation to transient and voltage stability are discussed.

2.4 SWIS stability

For Western Power to provide a reliable service, the SWIS must remain intact and be capable of withstanding a wide variety of disturbances. Therefore, the SWIS has been designed and operated to allow for contingencies to minimize the impact of disturbances.

This is so that a disturbance does not cause the network to become unstable, as the loss of stability may result in uncontrolled, widespread power interruptions. Thus, it is vital that disturbances and the theory of stability are understood.

2.5 Disturbances

In relation to power systems, a large disturbance is one for which the nonlinear equations describing disturbances dynamics cannot be linearised for analysis. Examples of these are transmission system faults, sudden load changes and the loss of generating units or transmission line outages [3].

A small disturbance occurs when a power system operating in a steady state condition undergoes a change in which case it can be analysed by the linearised versions of its dynamic algebraic equations. This could be a change in voltage regulator tap or the outage of a distribution line.

The reader should note the small disturbance definition, as a small disturbance will be used in the transient investigation of this thesis.

There are two types of stability investigations that evaluate the impact of power flows and disturbances on the distribution network. These are steady state investigations and transient investigations.

2.6 Steady state stability

A power system is in a steady-state operating condition, if all the measured or calculated quantities of the system are constant for analysis. When operating in a steady-state condition, if a sudden change in parameters of the system occurs, then the system has undergone a disturbance. Disturbances can be large or small depending on their origin [4].

The power system is “steady-state” stable, if it returns to a satisfactory steady state condition following a small disturbance. For the purpose of analysis the satisfactory voltage is stipulated by the SWIS voltage limits under emergency conditions. As outlined is section 2.3, these are 0.9 to 1.1 per unit.

2.7 Transient stability

Transient stability investigations are commonly undertaken by Western Power’s planning departments. These ensure the proper dynamic performance of the system and that the generator adheres to the Western Powers connection criteria.

Following a large or small disturbance, if a significantly different but satisfactory steady state operating condition is attained, then the system is “transiently” stable [4].

2.8 Voltage stability

The term 'voltage stability' is described as "the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a small disturbance" [4].

A system enters a state of voltage instability when a disturbance, increase in load demand, or change in system condition causes a progressive and uncontrollable collapse in voltage.

The main factor that causes voltage instability is the inability of the power system to meet the demand for reactive power.

Voltage instability is essentially a local phenomenon; however, its consequences may have a widespread impact. 'Voltage collapse' is more complex than voltage instability and is usually the result of a sequence of events accompanying voltage instability. Voltage collapse leads to a low voltage profile in a significant part of the power system [4].

Within this thesis, the analysis of voltage stability has been limited to the A1 distribution network. However, as stated before, in complex power systems such as the entire SWIS, many factors contribute to the process of voltage collapse because of voltage instability. These are the strength of the transmission and distribution system, power transfer levels, load characteristics, generator reactive power capability limits and characteristics of compensating devices [4].

After discussing stability, it is vital to outline how wind generation impacts on it. The relevant issues that attribute to wind generations impact are different to those of fossil fuel generation. This is because the wind resource is not always constant and the best wind resources are usually in remote locations where the strength of the distribution network is weak. Also, different wind generation technology is used and not all of these technologies can provide voltage control and network support.

2.9 *Wind generations impact on stability*

Wind energy generation main impacts on stability can be attributed to the following:

- Wind site locations
- Connection at lower voltage levels
- Wind Fluctuation
- Limited predictability

Historically, wind resources and hence wind energy generation are usually located at different locations than conventional power stations. The best wind generation site can also be the worst to transport electricity from as these sites are often remote and at a weak point of the SWIS. At weak points in the SWIS the fault level is low. This results from the high impedance at that point in the network. Therefore, if the wind farm participates in voltage support, then the ability to distribute the generated active or reactive power is limited by this high impedance.

Power converter coupled wind generators, like the A1 Wind Farm, are usually connected to lower voltage levels than conventional power stations. At lower voltages wind generation cannot participate in the control of stability at a transmission level, however, these can contribute to the control of voltage stability at a distribution level. This means that if there is a fault on the transmission network, then the A1 Wind Farm will not be able to impact on the stability of the transmission network.

The fluctuating nature of wind power could be perceived as a problem for voltage system stability. However, for large wind turbines, the wind generation output variations of minutes are slow in comparison to the voltage stability time frame of seconds [5]. Although, if the active power output of the A1 Wind Farm dropped below 20%, just before or during a fault, then this would limit its ability to supply reactive power and voltage support. This is because, at less than 20% of its output, the reactive power supplied is proportional to the active power output. This is discussed in more detail in section 3.7.1.

Systems with a high amount of wind power penetration usually require a higher spinning reserve than power systems utilising only fossil fuel generation. This is because of the limited predictability of wind speed and thus, the limited predictability of the output. Therefore, the higher the wind power penetration into the SWIS or the A1 distribution network, then the higher the influence that the wind fluctuations will have on the stability of other generators within the SWIS and A1 network [5].

Now that the thesis background has been discussed, the investigation into the A1 Wind Farms and surrounding network can be outlined. Section 3 will outline the A1 distribution network structure, the A1 Wind Farm and utilisation of ENERCON'Ss variable speed, synchronous generator, power converter coupled concept.

It is important to outline the A1 distribution network structure and the A1 Wind Farm, to understand what is needed to be modelled for the steady state and transient investigations.

3 The A1 distribution structure and AWF

The network chosen for the case study is the A1 distribution network.

The A1 network was chosen because it met the following characteristics:

- Utilised power converter coupled wind generation technology (ENERCON wind turbines)
- Wind energy generation was on a distribution network voltage level (22kV)
- The A1 distribution network was in a remote location
- Specific steady state and transient voltage stability studies had been performed by Western Power, therefore, this thesis could be compared and validated.

3.1 A1 distribution structure

The A1 distribution network (ADN) comprises of the 132/22 kV A1 zone substation. It supplies power to the local town and the surrounding district. It is supplied by two 132kV lines from the M1 power station and there are three large 132/22kV transformers that transform the voltage from transmission levels to distribution levels.

There are two 20MVA transformers (T1 and T3) and one 24 MVA transformer (T2). The normal mode of operation for the transformers is for 2 transformers to run in parallel, with the other on stand-by. However, due to high loads during summer and winter, it is necessary to switch 3 transformers into service during peak periods. As shown in Figure 3, the A1 Wind Farm high voltage feeders connect to the 22kV busbar of the transformer 1 (T1).

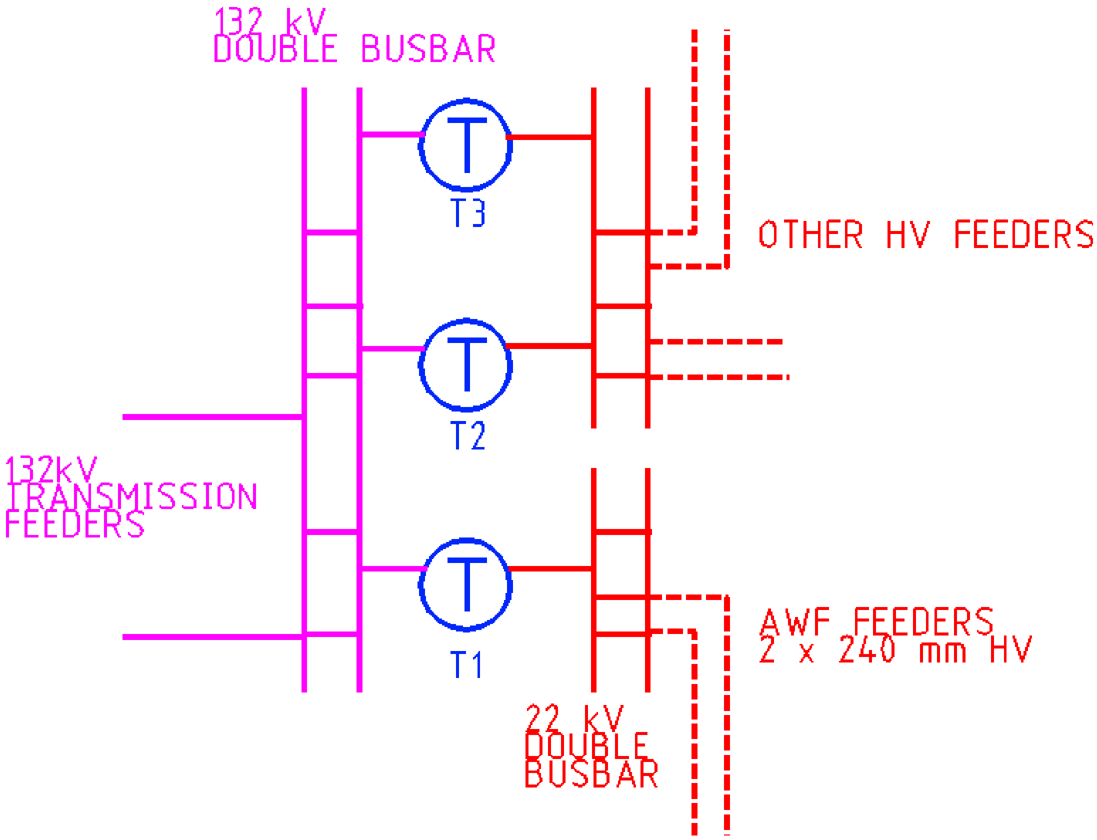

Figure 3: A1 zone substation layout

3.2 Substation loads

The peak substation load for the ADN occurs in winter as it is a colder climate that draws high heating loads. Peak load is expected to be around 6pm with the 2009 peak being on the order of 40MW. Figure 4 shows the peak load in 2009 reached just under 49 MVA (44.28 MW, PF=0.9) and the peak load forecast for the ADN is set to reach 51 MVA in 2010. From Western Power records the minimum load is around 13MW and occurs between around 2am and 5am [1].

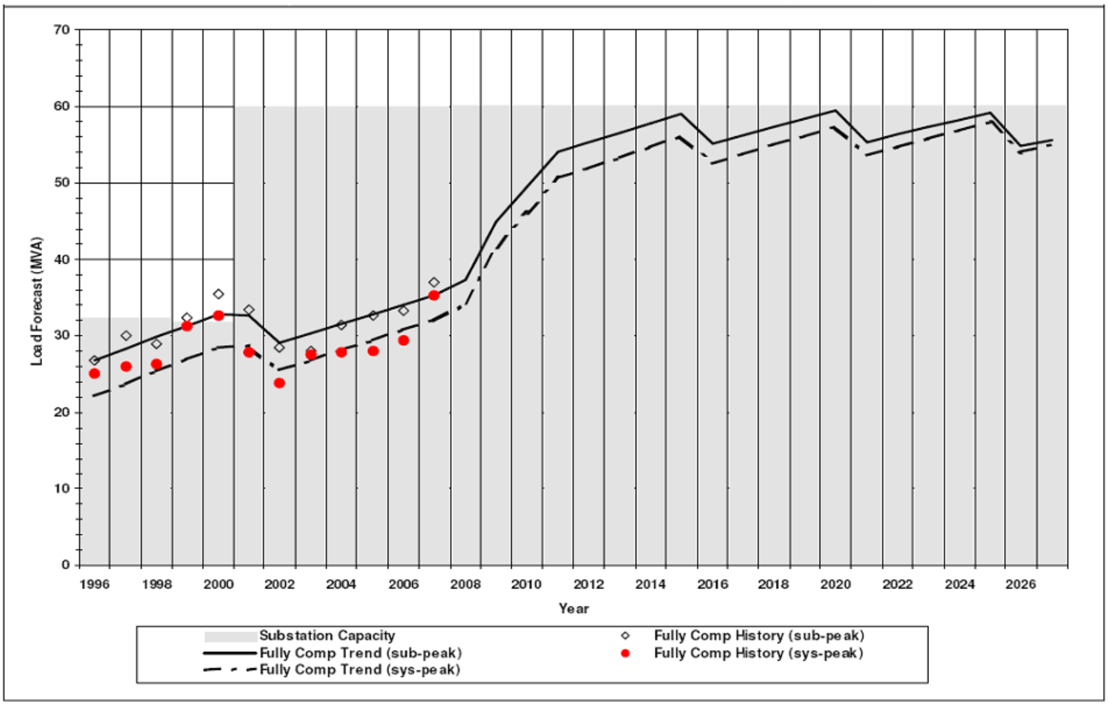

Figure 4: A1 peak load forecast 1996 to 2027 [1]

Figure 4 shows a large increase in growth from 2008 to 2012. This can be attributed to a large increase in the town population due to significant migration and a resource boom within the region. However, the growth rate is expected to level off after 2014 as the availability of housing decreases, this in turn causes a decrease in the migration and industry growth rate.

The peak and trough substation loads are important for creating the worst case scenarios for the steady state and transient investigations. Using the information above, an average peak load of 40MW and trough load of 10MW was decided upon to test the worst case scenarios.

As previously stated, the A1 Wind Farm is connected to the 22kV busbar of the A1 zone substation via A1 Wind Farm feeders. These feeders are important as this thesis investigates power flows on the A1 Wind Farm feeders specifically.

3.3 A1 Wind Farm feeders

For the A1 Wind Farm (AWF) to distribute power to the ADN efficiently, it requires dedicated High Voltage (HV) feeders from the AWF all the way back to the 22 kV busbar. From the A1 zone substation circuit breakers, there are two 12km HV feeders that run directly to the AWF. The cables that are used for the feeders are 240mm^2, 22kV, termitex, underground copper cables (termitex protects against termites).

Due to the charging capacitance associated with underground cables, these feeders act as a capacitive load over low load periods. Therefore, during low periods the AWF would have to absorb reactive power to reduce the voltage rise caused by this capacitive load. This will be discussed further in section 5.

3.4 A1 Wind Farm

The A1 Wind Farm consists of twelve ENERCON wind turbines rated at 1800kW each. ENERCON wind turbines are constructed using variable speed, pitch controlled, power converter coupled, direct drive synchronous wound rotor generator technology.

It generates power according to the wind speed at any particular time, but during commissioning it was limited to a maximum output level of 15 MW. This was specified by Western Powers Networks Development from system investigations [6].

Also during commissioning, the wind farms power factor was fixed at a value specified by Western Powers Networks Planning Development. Therefore, the reactive power generated and absorbed by the A1 Wind Farm is proportional to active power and power factor.

The maximum active power and power factor set-points have been determined such that the wind farm is able to provide the maximum possible generation benefit to the wind farm owner, while ensuring that the transmission network operates within the Transmission Planning criteria.

3.5 ENERCON wind turbines

ENERCON wind turbines are constructed using three rotor blades, upwind, direct drive synchronous wound rotor generator decoupled from the grid via a power converter. The power converter is essentially a rectifier, a dc to dc converter and a pulse width modulating inverter [7]. It uses three insulated gate bipolar transistor (IGBT), pulse width modulating inverters per turbine.

The ENERCON power converter allows the AWF to operate at an optimum value independent of the operating conditions. This would not be possible if the synchronous generator is directly coupled to a grid system at 50Hz, as the grid requires constant synchronous speed. By using the power converter to rectify and then invert the generator output, the ENERCON concept allows the generator turbine speed to vary. This optimizes the efficiency of power generation and gives it the ability to provide full reactive power control [9].

3.6 Power converter coupled generator construction

The synchronous generator (SG) utilised by the ENERCON turbine is a multiple salient pole, electrically excited, direct drive, using wound rotor generator technology. The synchronous generators excitation power flows to the stator via the control of a power converter. Thus, unlike conventional synchronous generators, the stator is not directly coupled to the grid but to the power converter. Therefore, the reactive power exchange with the grid is not determined be the properties of the generator but by the control of the power converter.

By decoupling the SG from the grid, it allows the power converter to operate at a power factor that best suits the operating conditions of the A1 distribution network.

This means that the power factor of the generator and converter can be controlled independently [9]. The operation and control of the power converter will be discussed further in section 3.7..

Figure 5 shows the configuration of the direct drive power converter coupled generator.

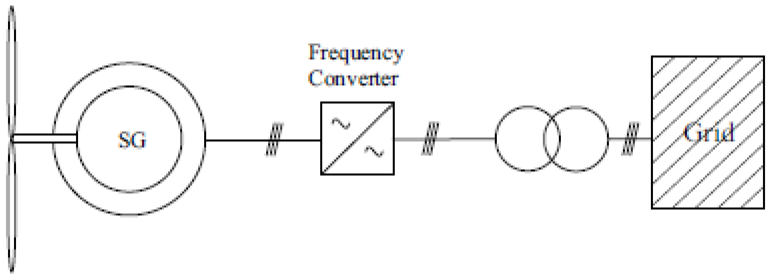

Figure 5: Direct-drive power converter generator [9]

Figure 5 shows that the three blade rotor and generator shafts are mounted to the same shaft without the use of a gearbox. The omission of a gearbox requires that a synchronous generator has a large number of poles. These multiple poles allow the generator to operate at low speeds.

The multiple poles of a generator make the nacelle (hub) of the turbine larger than other turbine types. Therefore, its aerodynamic egg shape is important to minimize the turbulence around the base of the blade, thus, increasing performance.

The generator is connected to a 415/22 kV 2 MVA step transformer, via three 700kVA IGBT inverter modules (power converter).

3.7 The power converter

The power converter allows the AWF to participate in maintaining the quality of supply and power system stability. It provides the AWF with robust fault ride through capabilities, voltage control and management of active and reactive power [10].

3.7.1 Power converter operation performance

The provision and control of reactive power for voltage control purposes is one of the main objectives of the AWF. This is known as Flexible Alternating Current Transmission Systems or FACTS.

Figure 6 shows the FACTS capabilities of ENERCON wind turbines.

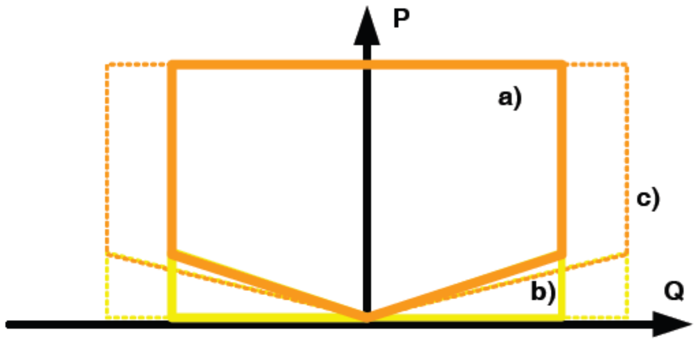

Figure 6: General capability chart of ENERON wind turbines with FACTS capabilities: a) default capability b) extended capability with the STATCOM option c) expanded capability with the Q+ option [11]

From Figure 6, it can be seen that the default option of the ENERCON wind turbine can provide a constant reactive power for the operation between 20% and 100% rated active power. However, ENERCON states that within 0% and 20% of rated active power output, the reactive power capability is proportional to the available active power [9].

The provision of reactive power from the ENERCON wind turbine can also be extended by installing a STATCOM; this is known as the STATCOM option. The installation of a STATCOM allows the provision of reactive power completely independent from the provision of active power and the availability of wind.
This option may be required in some remote areas where the standard ENERCON machine cannot address the reactive power capabilities required to connect that point of the network.

An expansion of the reactive power capability with the same dynamic performance is available with the Q+ option. This option is similar to the STATCOM option, however, its provision of reactive power has a wider range and is able to provide more reactive power to support the voltage following a fault or other dynamic event [9][12]. Therefore, unlike other wind energy conversion systems, the ENERCON wind turbines can provide reactive power and voltage support to the A1 distribution network. This is a desirable characteristic for Western Power.

3.7.2 Control of the power converter

The power converter is vital for voltage control and maintaining system stability. In order for the power converter to fulfil these functions, the appropriate control is required.

For the steady state investigations, the control of the power converter revolves around a fixed set point for power factor or reactive power. These set points result from Western Power planning studies and are set during the commissioning of the AWF.

Although that these set points are determined during the commissioning study, once the wind farm is in operational, these set points can be altered online via the wind farm control room or dispatch centre. This is all carried out via the supervisory control and data acquisition (SCADA) and additional communication interfaces. Power factor and reactive power set point control allows the reactive power capability from the AWF to maintain voltage control [11]. Based on the difference between actual voltage and voltage set point, the Farm Control Unit (FCU) provides set points for reactive power, thus, the power factor is altered to achieve this reactive power setpoint.

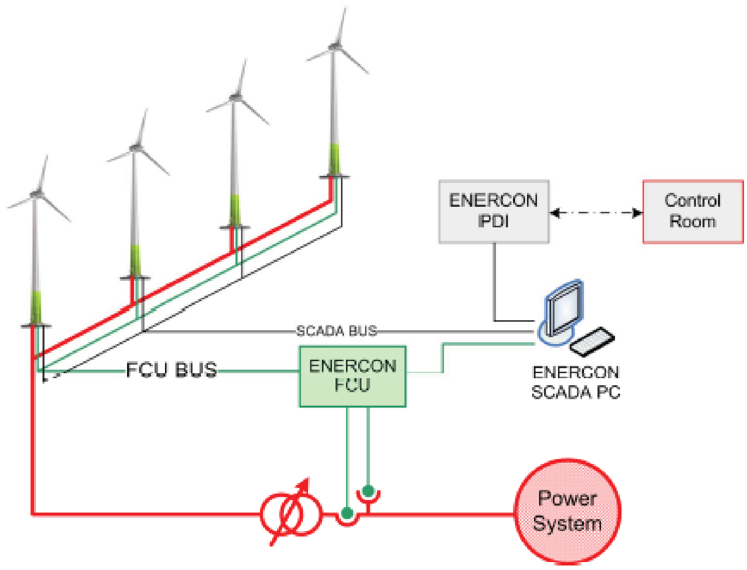

Figure 7: Structure of ENERCON farm Control Unit for wind farm voltage control [11]

Figure 7 shows the correlation between the AWF, the SCADA interface and the central control room. To achieve set point control, the central controller is provided with measurement values from the preferred measurement point. This is usually the point of connection to the network, and the set points are determined by the control room which is on the wind farm site [11].

However, the Western Power East Perth Control Centre, NOCC, controls the dispatch of all generators that connect to the SWIS network. It does this by sending a signal to the generators that capacity is available or needed at a certain point in the network. For the majority of the time the A1 Wind Farm generates its available capacity automatically. NOCC can control the capacity or set points manually, but, this is rarely done, if ever.

Therefore, unlike some other generators, the control circuit breakers and set point adjustment is fully automated by the farm control unit. Thus, when capacity and wind is available, the AWF is always connected and generating.

3.7.3 ENERCON fault ride through capabilities

Fault-ride-through (FRT) is a capability to withstand temporary voltage dips caused by short circuits or faults. Depending on the distribution system, the requirements for the SWIS may vary depending on the identified needs and characteristics of the power system, for example, the installed generating capacity, load characteristics, earthing, protections, voltage and angle stability and fault levels [11].

Active and reactive power during faults or post fault is a specific requirement desired within Western Power distribution networks. This requirement is especially vital for distribution networks utilising wind generation. This is because usually good wind resources are available in remote, less populated areas with a weak power system infrastructure. Within these weaker distribution networks there is lesser ability to deal with various types of disturbances and to support the power system security and stability.

Therefore, as stipulated by section 3.3.3.3 (C) of the Western Power technical rules [2], fault ride through capabilities are required for all wind generators.

3.7.4 ENERCON under voltage ride through (UVRT)

ENERCON address the fault ride through requirements with its FACTS capabilities. Using the power converter and software, the Under Voltage Ride Through (UVRT) allows the AWF to ride through faults for up to five seconds at zero volts at its terminals, even at full rated active power.

It does this by using the inverter within the power converter to stay connected during depressed voltages. The insulated gate bipolar transistors within the inverter have high current ratings and are protected by current limiting protection. During UVRT, the inverter either continues to supply a limited output current with a depressed terminal voltage or ceases switching the insulated gate bipolar transistors while staying on-line (circuit breaker remains closed).

The use of a power converter system on variable speed inverter coupled turbines provides the option of maintaining load on the rotor generator during the depressed terminal voltages by switching in a dump load onto the DC bus.

During UVRT, a special UPS safely supplies all necessary auxiliaries to operate the AWF during the voltage depression, (e.g. controls, drives, fans).

The UVRT control mode is triggered by voltage levels of between 95% and 80% rated voltage. Section 3.3.3.3 (C) of the Western Power technical rules [2] stipulates that under voltage fault ride through capabilities are required for all generators.

3.7.5 A1 Wind Farm under voltage ride through (UVRT)

Under fault conditions, the A1 Wind Farm (AWF) continues to generate provided that the system voltage is maintained above the under voltage set point of the inverters. The under voltage set point is 80%. At this point the AWF reverts from constant PQ control to voltage control (controls AC voltage set point).

Therefore, after a fault has occurred the AWF will adjust the power factor to generate the most reactive power to quickly achieve the AC voltage set point.

Once the fault has been cleared, if the new steady state system voltage is below the voltage set point, then the inverters would switch themselves off line. The inverters can only reconnect 3 minutes after the system voltage has been restored to nominal levels.

UVRT is vital for the ADN as the loss of the wind farm during a fault condition may lead to an additional drop in system voltage during and following the clearing of the fault.

4 Network modelling approach

Section 4 discusses the approach to the modelling of the A1 distribution network and the A1 Wind Farm that was described in Section 3.

To model the ADN and AWF, data collection from the Western Power sources was necessary. The data collected is discussed as well as the construction of the PowerFactory (PFY) model. The network component models (cables, transformers) created within PFY to represent the WP distribution network, are also discussed briefly.

The PowerFactory model created by this thesis can be found in appendix B.

4.1 Data collection

Data collection for the PowerFacrtory model was collected from a number of sources. These are as follows:

- Manufacturers datasheets
- PowerFactory Training Manual
- Western Powers SWIS computer interface, DFIS

Manufacturer's datasheets were used for modelling the cables within the PFY model. To create an accurate representation of the cables within the ADN, the rated current, positive and zero sequence resistance and reactance was extracted and used. Please refer to appendix A for exact specifications.

The power factory training manual specified typical transformer and synchronous generator parameters. The manual outlined positive sequence impedance and copper losses for the transformer, and stator resistance and synchronous reactances for the synchronous generator. Please refer to appendix A for exact specifications.

DFIS is Western Powers SWIS, geographic information system. It provided conductor and cable lengths, sizes and connection points of equipment. This tool is very powerful for storing and retrieving the network data and its specifications.

A Western Power presentation [1] was utilised to determine actual loads and generation of the A1 Network over 2009. This data was entered into the PFY model to create the worst case scenarios for steady state analysis.

4.2 PowerFactory construction

Using the data collected, the PowerFactory simulation was constructed to represent A1 Distribution Network, including a specific “constructed” model for the A1 Wind Farm.

To construct the above, the following models were used from the PowerFactory (PFY) library:

- External Grid – To model the 132kV interconnecting grid
- Terminals – To model the busbars
- Transformers – Used to model zone substation, distribution transformers and point of interconnection between the AWF and ADN
- General Loads – To model static PQ loads
- Lines – To model the cables based on a data sheet
- Induction Machine – To model dynamic loads
- Synchronous generator – Mechanical to electrical energy converter, coupled to the SWIS via a power converter
- Power Converter – Modelled by a rectifier and inverter

The DC booster (modelled by a DC/DC converter) was not included in the PFY model as it did not alter any of the results and proved to be a source of error within PFY when using voltage control.

4.3 Models

Section 4.3 discusses the network component models created within PFY to represent the A1 distribution network.

4.3.1 External grid model

PowerFactory's external grid element was used to model the transmission network feeding the A1 zone substation. This is shown in Figure 8.

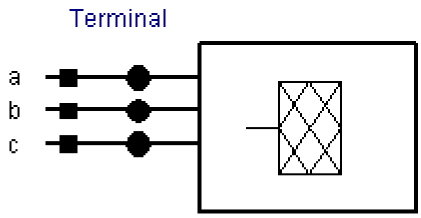

Figure 8: External Grid model [13]

Specifically for the A1 network, the external grid model simulates the two 132kV transmission lines from the M1 power station. The purpose of this model is to represent the transmission network and to have the ability to specify the fault current that the transmission lines provide during a short circuit or fault event.

According to the Western Power database the fault level is 326 MVA when both 132kV lines are operational. When one line is out of service then the fault level reduces to 120 MVA, therefore, the network is weaker in the event of a fault. The fault level input enables the simulation to represent realistic faults and the consequences on voltage stability.

4.3.2 Terminal model

Terminals represent the busbars within the SWIS network. These act as a point of interconnection between all models. The terminal's main function is its ability to isolate parts of the network easily. Thus, parts of the simulation can be switched in and out for variation of power flow studies. Another purpose of the terminal is to act as a virtual instrument so voltage and reactive power can be compared during transient simulations.

4.3.3 Transformer model

There are two types of transformer models within the PFY simulation of the A1 distribution network. These are the Delta – Delta model, used for the zone substation transformers and the Delta – Wye neutral model, used for the connection of the AWF to the A1 distribution network.

Transformer models contain absolute impedances, leakage reactance's, winding resistances and magnetization reactance. Each transformer model is defined by various inputs. These are as follows:

- Technology – Three phase
- Rated Power – 20 to 24 MVA
- Nominal Frequency – 50 Hz
- Rated Voltage – HV and LV side
- Configuration – Delta – Delta or Delta-Wye neutral
- Positive and Negative sequence impedance – Refer to Appendix A
- Zero Sequence Impedance – Refer to Appendix A
- Magnetizing Impedance – Refer to Appendix A

Figure 9 shows the Delta – Delta transformer model. This configuration has no neutral as the HV network is delta configuration.

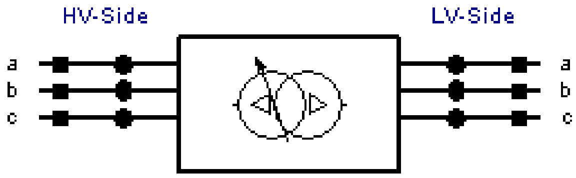

Figure 9: Delta – Delta transformer model [13]

Figure 10 shows the Delta – Wye neutral transformer model. On the low voltage side, this configuration has its star point connected to ground and the neutral wire. This is known as the main earth neutral (MEN). This is when all the neutrals are bonded to the main earth as per the requirements of the Australian Wiring Rules, AS3000 [14]. This is because of the phase imbalance on the low voltage side of the transformer. This imbalance results in neutral currents and the potential for large zero sequence fault currents.

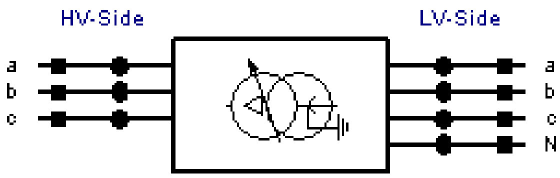

Figure 10: Delta – Wye neutral transformer model [13]

4.3.4 General load model

Figure 11 shows the balanced three phase PQ load model implemented in the PFY simulation. This model represents the HV PQ load seen at the 22kV busbar.

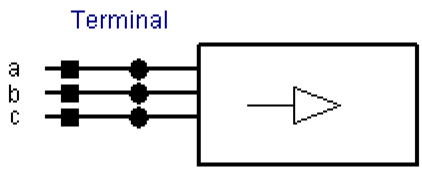

Figure 11: Balanced three phase PQ load model [13]

The inputs that are specified within this type of load are as follows:

- Real power (P)
- Reactive power (Q)

4.3.5 Induction machine model

Figure 12 shows the balanced three phase induction machine model implemented in the PFY simulation. This model represents the motor load seen at the 22kV busbar. This model is important for testing the transient analysis of the A1 distribution network, as its load is dynamic unlike the static general load model.

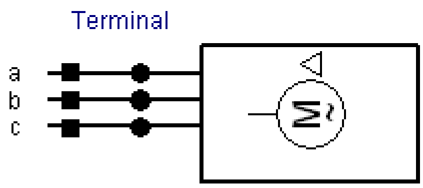

Figure 12: Three phase induction machine model [13]

The following parameters were specified for each induction machine:

- Rated Voltage – 22kV
- Input mode –Electrical Parameters
- Power Rating – Rated mechanical power of 4000kW
- Nominal Frequency – 50Hz
- No of Pole pairs – 1 pole pairs
- Connection – Delta

The default parameters within PFY were utilised for the rotor and the stator within load flow and the short circuit analysis.

4.3.6 Line model

Figure 13 shows the HV line model used to represent the 22kV HV feeder cables within the PFY simulation.

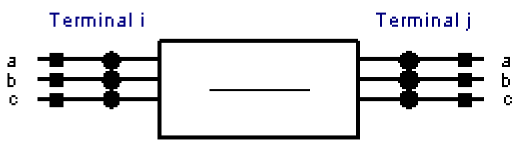

Figure 13: HV Cable models [13]

Originally the model was constructed using the datasheet in Appendix A. But when the simulation was tested it was found that this model produced unrealistic power losses. These losses accounted for half the amount generated from the AWF. It can be concluded that these losses can be attributed to high zero, positive and negative reactance values within the data sheet. Therefore, the model was altered using data from the Western Powers design software LV design.

The data used from this software can be found in appendix A.

Within the line model, the following parameters are specified:

- Rated current – 479 A
- Positive, Negative and Zero sequence resistance - 0.161 ohms/km
- Positive, Negative and Zero sequence reactance - 0.067 ohms/km
- Length of the line in kilometres – 12 kms

This thesis does not investigate unsymmetrical faults, thus, the zero sequence impedance is irrelevant.

4.3.7 Synchronous generator model

Figure 14 represents the synchronous generator model used the represent the multiple salient pole generator utilised by the ENERCON wind turbines.

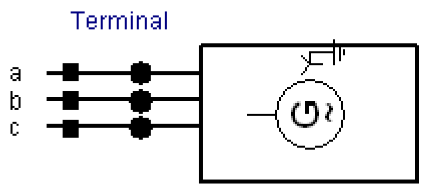

Figure 14: Synchronous generator model [13]

For the AWF, all twelve 1800 kW wind turbines have been grouped in this lumped generator model. The synchronous generator represents the part of the ENERCON wind turbine which converts the mechanical energy of the 3 rotor blades into electrical energy.

The synchronous generator is specified by the following parameters:

- Nominal apparent power – 22.73 MVA
- Nominal Voltage – 415 V

- Power Factor – 0.95 leading

For load flow, the following parameters have to be specified:

- Mode of Local Voltage Controller – Power Factor
- Active power – 15 MW
- Reactive power – -4.93 MVAr
- Synchronous reactance's – Xd = 2.61 pu, Xq = 1.57 pu
- Inertia – The acceleration time constant of 4 seconds

To represent the ENERCON model accurately, the synchronous generator is coupled to a power converter. The power converter is constructed of two models within PFY, these are as follows:

- Rectifier
- Pulse width modulator inverter

4.3.8 Rectifier model

Figure 15 represents the rectifier model used to construct the power converter model within the PFY simulation.

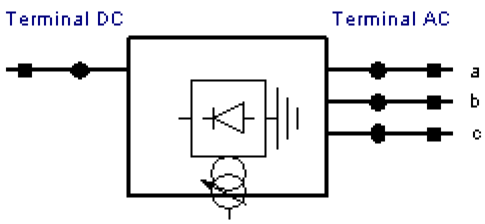

Figure 15: Rectifier model [13]

This model is specified by the following parameters:

Rated AC voltage - 415 V

Rated DC voltage -560 V

Diode / Thyristor converter - Diode

Built in transformer – Default turns ratio

4.3.9 Inverter model

Figure 16 represents the pulse width modulator inverter model used to construct the power converter within the PFY simulation.

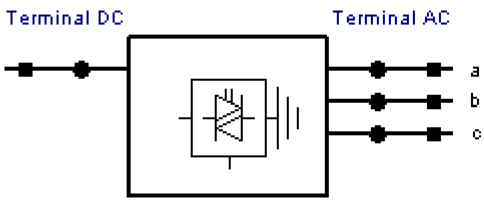

Figure 16: Pulse width modulator inverter model [13]

This model is specified by the following parameters:

Rated AC voltage - 415 V

Rated DC voltage -560 V

Rated power – 37.8 MVA

Modulation – Sinusoidal PWM

Control Mode

Steady State – P-Q (constant PQ control)

Transient – Vac-phi (AC voltage set point control)

The combination of the synchronous generator, the rectifier and the pulse width modulator inverter within the PFY simulation represents the A1 Wind Farm model.

This model will be referred to furthermore as the “constructed” AWF model [9].

Figure 17 on next page shows the entire A1 distribution network and the A1 Wind Farm model created within PowerFactory.

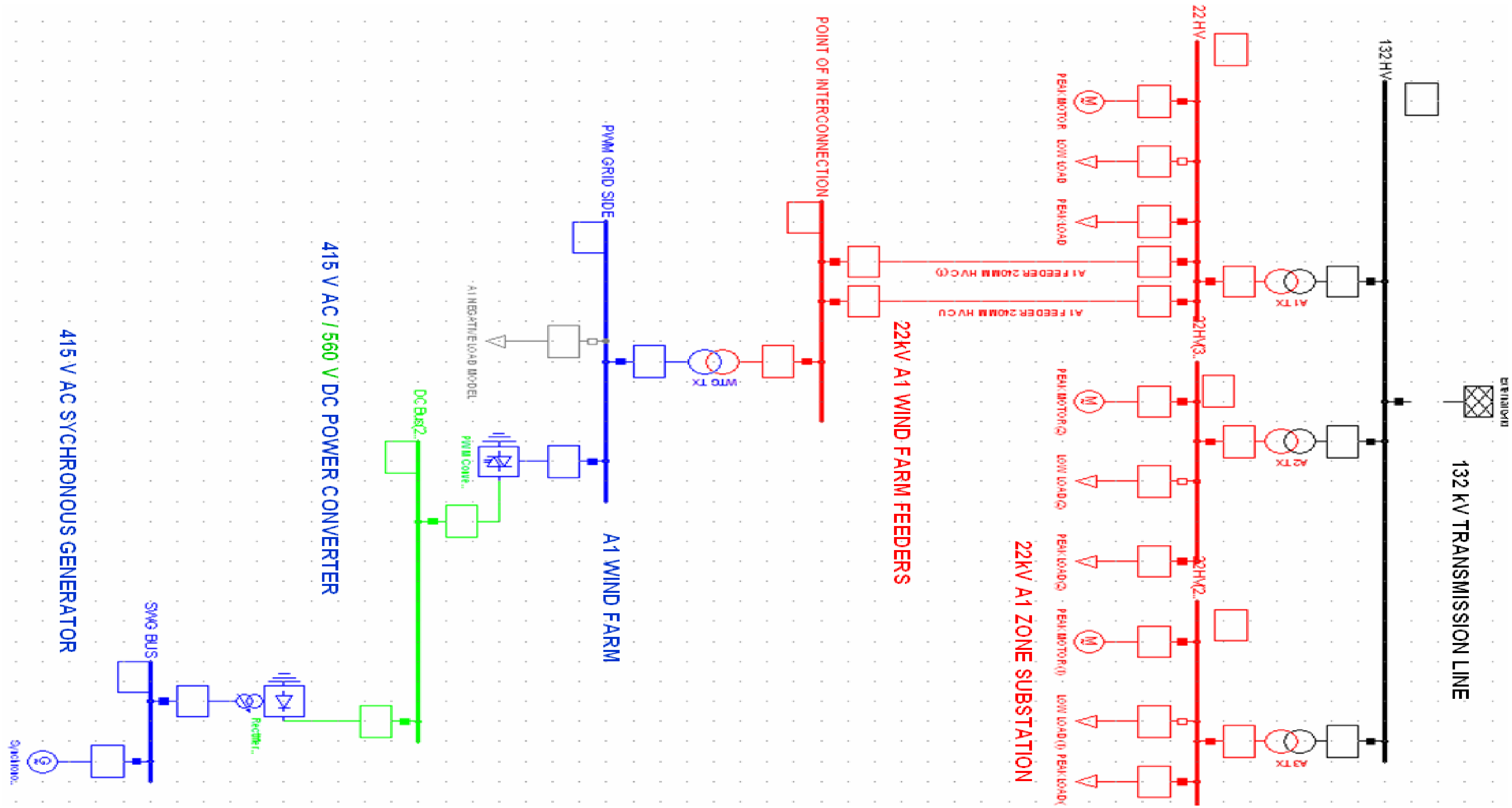

Figure 17: A1 distribution network and the A1 Wind Farm model created within PowerFactory.

5 Testing the PowerFactory simulation

Once the PowerFactory simulation model was constructed, the steady state and transient investigations were undertaken. These studies investigated the voltage that resulted from the power output and control of the A1 Wind Farm.

5.1 Steady state investigations

During the initial commissioning of the A1 Wind Farm, the power factor and maximum active power set points were determined by the Western Power planning department. The objective of these set points were to ensure that the operation of the wind farm would have minimal impact on the 22kV busbar voltage at A1 zone substation. By limiting the A1 Wind Farms (AWF) output, any adverse voltage fluctuations, due to the change in output, would have minimal effect on Western Power customers connected to the same 22kV busbar.

This meant that any reactive power support from the AWF would be a function of the active power and power factor.

The steady state investigation within this thesis has utilised the same method as the Western Powers planning department. The purpose is to determine a maximum active power set point for the wind farm and an optimum power factor to minimize the AWF's impact on voltage fluctuations at the 22kV busbar. The set points for the active power was determined by the Western Power study [6] to be 15MW, while the power factor set points were altered between 0.95 leading to 0.95 lagging, as these are the limits of the technical rules [2].

5.1.1 Determine maximum active power output from the A1 Wind Farm.

One of the objectives of limiting the active power and hence the reactive power of the AWF would be to limit the number of tap changes at the A1 zone substation when the wind farm is operating. This would ensure that additional maintenance of substation tap changer was avoided (due to additional voltage regulation). The aim of the active power limits is that the number of tap changes at the zone substation will be similar to that which would have occurred if the wind farm was not connected.

Also under the steady state investigation, the optimal tap position for the A1 zone substation has been investigated. This ensured that the reactive power support of the AWF will not be at its limit and would act as a secondary voltage control measure to the tap settings. This way, if a fault does occur, then the tap position will not be too far away from its optimal position and the AWF will be able to provide more reactive power support to recover the system voltage.

The optimal tap position for the A1 zone substation would be the position that resulted in the least amount of tapping and voltage fluctuations. Ideally the optimal tap position would be the neutral position, thus, giving the substation its full range of voltage control by tapping. At the A1 zone substation, each tap position up or down results in a 1.25% change in the busbar voltage. Thus, if the voltage was 1.0 per unit and the tap position changed from the neutral position (zero) to tap 1, then this would result in a voltage of 1.0125 per unit or 1.0125 times 22 kV.

However, having the tap position at neutral would mean that voltage regulation would solely rely on the reactive power support of the AWF and the 132kV feeders. This is another reason why it was important to determine the active power limit of the AWF during commissioning. Determining this would allow Western Power planners to determine the A1 Wind Farms consequent reactive power support and the tap position for steady state conditions.

The Western Power planning study concluded that large active power output fluctuations of the AWF would increase the tap changer activity at the A1 zone substation. That is additional tap changer activity would add to the risk of the tap changer being further from the optimal tap position during a fault.

Therefore, by limiting the AWF output to 15MW, the tap changer position would closely follow that which would be expected without the wind farm in operation. Thus, this would reduce the tap changing activity and voltage fluctuations. However, by limiting output even further, this produced better results, but the improvement was considered to be too marginal to justify the extra limitations [6].

Concluding, all future steady state and transient investigations have been conducted with the limiting wind farm maximum active power output set to 15 MW.

5.1.2 Preferred A1 Wind Farm power factor

As the active power limit of 15MW had been determined, a preferred power factor would have to be investigated to determine the reactive power generated or absorbed by the AWF.

This is because the power factor of the loads and generators connected to the SWIS directly relates to its voltage fluctuations and voltage control.

The term power factor (PF) is a function of the cosine of the phase angle difference between voltage and current. Thus:

$$\text{Power Factor} = \text{cosine}\,(\theta v - \theta i)\ [8]$$

θv = Voltage phase angle in degrees.

θi = Current phase angle in degrees

For power system analysis, the convention is that generators with a lagging power factor generate reactive power, and that these generators supply inductive loads [8]. Whereas generators with a leading power factor absorb reactive power, and that these generators supply capacitive loads.

Figure 18 summarises the convention and how it relates to power converter (inverter) coupled generation.

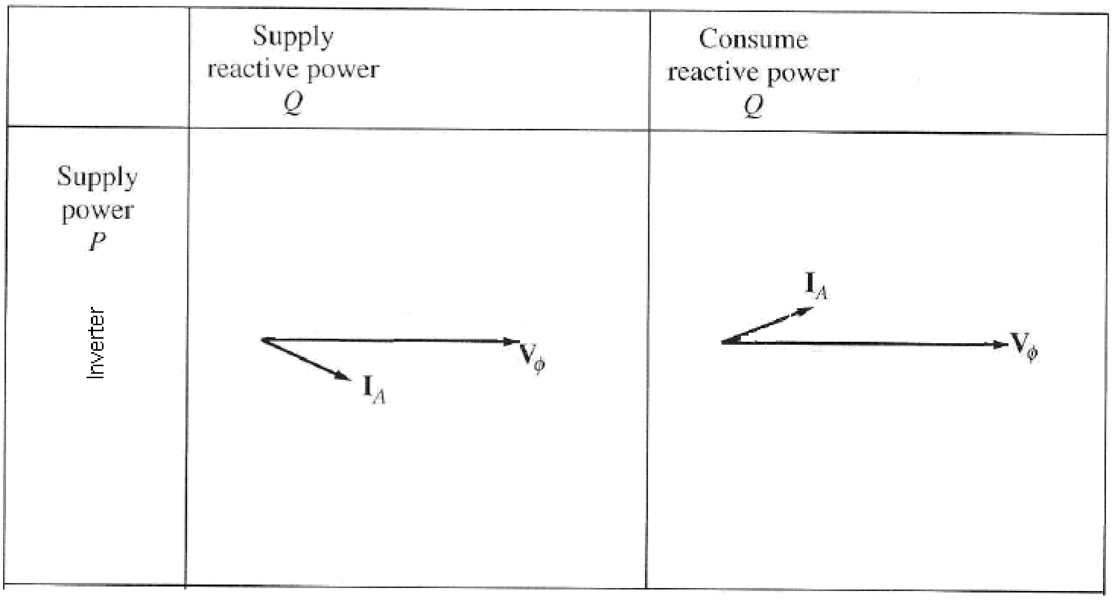

Figure 18: Inverter theory in relation to power factor [adapted from 16]

Figure 18 shows that when supplying active and reactive power, the inverter coupled generators current (I_A) lags the terminal voltage (V_Φ), therefore the PF is lagging and the generator is producing reactive power. However, when supplying active and absorbing reactive power then the inverter coupled generators current (I_A) leads the terminal voltage, therefore, the PF is leading.

This same convention can be applied to loads, however, the passive sign convention must be applied. Therefore, loads with a lagging power factor absorb reactive power, these are known as inductive loads, for example induction motors. While loads with a leading power factor generate reactive power, these are known as capacitive loads. Although capacitive loads are rare, capacitive load conditions often occur during low load periods, for example midnight. This results from the lack of active and reactive power being drawn on the distribution and transmission network and the line charging current of very long lines or cables.

Generators that generate reactive power increase the voltage magnitude within the SWIS, while generators that absorb reactive power, decrease the voltage magnitude within the SWIS. As loads are the opposite of generators, loads also behave opposite of the above. For example, capacitive loads such as the line charging example result in a voltage rise over the distribution line.

An increase and decrease in the voltage results from the impedance of the SWIS. The SWIS is an inductive network, therefore, its impedance is $j\omega L$. As loads or generators generating reactive power have an impedance of $-j(1/\omega C)$, then by multiplication, this will result in a positive number and a voltage rise ($j \times -j = 1$). Whereas, if the load or generator absorbs reactive power have an impedance of $j\omega L$, then by multiplication this will result in a negative number and a voltage drop ($j \times j = -1$).

Therefore it can be concluded that, the power factor of the loads and generators connected to the SWIS directly relates to its voltage fluctuations and voltage control.

To determine the preferred power factor for the operation of the wind farm, the power factor was altered to investigate its effect on busbar voltages. This was done by devising two worst case scenarios for the substation load and A1 Wind Farm generation. The two worst case scenarios are as follows:

Scenario 1 - Minimum A1 Wind Farm output of 1 MW and a peak substation load of 40 MW.

Scenario 2 - Maximum A1 Wind Farm output of 15 MW and a low substation load of 10 MW

To replicate the Western Power steady state study, the load was split into general static load and motor load. The static load was assumed to be 70% of the total load and its power factor 0.99 lagging. And the motor load was assumed to be 30% of the total load and a power factor of 0.8 lagging. Thus, both were inductive loads that would absorb reactive power.

The impact on the busbar voltage was tested in both scenarios by varying the AWF generators power factor from 0.95 leading to 0.95 lagging. This was done by changing the output of the inverter within the power converter as this directly controls the A1 Wind Farms output.

Before the AWF was connected, the steady state per unit voltage at the 22kV busbar was 0.986 per unit.

Therefore the power factor that produces the voltage closest to 0.986 per unit will be the optimal power factor.

The steady state test results are summarised in table 1.

Table 1: Steady state optimum power factor test

SCENARIO	WIND PF	LEADING OR LAGGING	VOLTAGE AT 22kV BUSBAR (kV)	VOLTAGE AT 22kV BUSBAR (pu)
1	0.95	LEADING	21.738	0.988
1	1	NA	21.757	0.989
1	0.95	LAGGING	21.775	0.990
2	0.95	LEADING	21.697	0.987
2	1	NA	22.04	1.000
2	0.95	LAGGING	22.251	1.012

5.1.3 Scenario 1 Analysis (A1 Wind Farm output = 1MW, Peak load = 40MW)

In scenario 1, the AWF output was limited to 1 MW and the total zone substation was set to a peak load of 40MW. The power factor (PF) of the power converter was altered from 0.95 leading the 0.95 lagging. This resulted in the reactive power output of the power converter changing from absorbing to generating 0.33 MVAr.

Table 1 outlines that a PF of 0.95 lagging had the most affect, in comparison to 0.986 per unit, on the 22kV bus voltage resulting in a bus voltage of 0.99 per unit at peak load. Table 1 also proves that a PF of 0.95 leading had the least impact on the bus voltage with a voltage of 0.988 per unit. As the loads are the same for this test, both voltage fluctuations can be attributed to the absorption and generation of the reactive power by the AWF controlled by the power converter and the changing power factor. Neither of these would result in a tap change at the A1 zone substation as all voltage fluctuations are well within the 1.25% voltage step size per tap.

5.1.4 Scenario 2 Analysis (A1 Wind Farm output = 15MW, low load = 10MW)

In scenario 2, the AWF output was increased to 15 MW and the total A1 zone substation set to a low load of 10MW. The power factor (PF) of the power converter was altered from 0.95 leading to 0.95 lagging. This resulted in the reactive power output of the power converter changing from absorbing to generating 4.93 MVAr.

Again the results in Table 1 prove that PF of 0.95 lagging had the most affect on the 22kV busbar voltage, resulting in a bus voltage of 1.012 per unit at low load. This is known as voltage rise, and may impact customers by providing higher voltages that are outside the limits of typical appliances. Voltage rise can be just as much of a problem as under voltage, as it can cause premature appliance failure and customer complaints.

From Table 1 it can be concluded that the power factor of 0.95 lagging would result it additional tapping down. Therefore, it would also require tapping up once the AWF output dropped off.

In scenario 2, the PF of 0.95 leading also had the least affect on voltage as it resulted in a voltage of 0.987 per unit (closest to 0.986 per unit). This would require no additional tapping at the zone substation and would result in the least amount of steady state voltage fluctuations.

At a low load and high output, the PF of 1.0, absorbing or generating 0 MVAr by the AWF resulted in a voltage rise on the busbar voltage, as this increased to 1.0 per unit. At this power factor the A1 zone substation would require additional tapping down at high wind farm generation and tapping up again at low generation. This is not desirable as it increases voltage fluctuations and tap changer maintenance.

5.1.5 Optimum power factor at steady state

In conclusion of the steady state investigation, it is apparent that a power factor of 0.95 leading is optimum for both cases as this maintained the voltage closest to the original 22kV busbar voltage (0.986 per unit).

In reality the AWF peak output occurs at night and as explained before, this also coincides with low loads on the A1 distribution network (ADN). These low load conditions already result in voltage rise on the AND. This voltage rise can be attributed to the voltage rise over distribution and 132kV lines.

Therefore, using a PF of 0.95 leading (absorbing reactive power) would reduce the voltage rise caused by the capacitance of the 132kV feeders while also resulting in the least impact on voltage fluctuations and tap changing.

In general, the overall A1 distribution network has a high resistance to reactance ratio (R/X), therefore, it is apparent that from 22 kV busbar at the A1 zone substation to the customers load the voltage would drop, due to conductor resistance. This voltage drop is a function of the I^2R losses due to the active power drawn. Although, as the active power draw is low during these load and generation conditions, the impact of voltage drop would be negligible to Western Power customers at this time.

Therefore, analysing the steady state results it can be concluded that for both scenarios, a fixed power factor for the AWF should be set to 0.95 leading. This would result in the least impact on the customers in both scenarios due to the voltage rise in the distribution and transmission network. This voltage rise would be balanced by the AWF absorbing reactive power, thus, reducing the voltage.

To validate the above conclusion the Western Power steady state study [6] concluded that when using fixed power factor mode, a leading power factor resulted in a lower impact on the A1 substation voltages than a lagging power factor. The results also showed that while using a power factor of 0.95 leading, the wind farm had the least affect on A1 zone substation 22kV busbar voltages.

It can also be concluded that AWF is a major influence on voltage control within the A1 distribution network. This is because that any small voltage change can result in additional tapping and voltage fluctuations at the 22kV busbar.

Therefore, it is recommended that all voltage rises caused by the wind farm and capacitive line is mitigated by a leading power factor.

5.1.6 A1 Wind Farm model steady state behaviour

For the steady state analysis, the “constructed” AWF model within PowerFactory behaves like a generator with a fixed active power output and power factor. These parameters are stipulated in PowerFactory using the inverter within the power converter model. Therefore, as long as the stipulated active and reactive power parameters are within the synchronous generators power limits, the power converter controls the output of the “constructed” AWF model. It can then be concluded that the synchronous generator reactive power capabilities apart from its limits, have no influence on the steady state investigation.

Therefore, the synchronous generator reactive power capabilities will not have any impact on the network. This is because the generator is decoupled by the power converter, and at steady state, the reactive capability of the power converter is the only parameter that has an impact.

It can then be concluded that the “constructed” AWF model behaves essentially as a negative load at steady state. A negative load model is when a load is used to simulate a generator. In PowerFactory, the positive direction of the load is from the grid towards the load. Thus, if the load is negative then it is essentially generating active and reactive power.

For both models the active power output and power factor are determined, and a resulting reactive power is generated or absorbed using the following formulas:

Active Power (P) (given) = 15MW

Power Factor (given) = 0.95 leading

Apparent Power (S) (calculated) = 15MW / 0.95 = 15.78 MVA

Angle between voltage and current (θ) (calculated) = cosine^-1 x 0.95 =18.19º

P = 15.78 x cosine (18.19º)

= 15 MW

The resulting reactive power from the above:

Q = 15.78 x sine (18.19º)

= 4.93 MVAr (A1 Wind Farm absorbing reactive power)

To follow power system analysis convention, active power must be negative for the load to be generating. However, for loads, a leading power factor results in a capacitive load (lagging generator) and generating reactive power, while a lagging power factor results in an inductive load and absorbing power factor. Therefore, a negative load requires a lagging power factor to replicate a leading generator.

5.1.7 Conclusions of steady state investigation

Concluding the steady state investigation, it was determined that operating the AWF at a limited active power output of 15MW and a power factor of 0.95 leading would result in the least voltage impact on Western Power customers. This limited active power and power factor control (PQ) would also result in the least amount of tap changers with a changing load and AWF generation, thus, reducing maintenance and more importantly the voltage fluctuations. This power factor set point will also absorb reactive power to compensate for the voltage rise in the capacitive distribution and transmission line during low load conditions.

It can also be concluded that AWF has a major influence on voltage control within the A1 distribution network. As a small voltage rise from the wind farm can lead to significant implications for the control voltage via tap changing.

While using a fixed PQ control for the “constructed” AWF model, it acts like a negative load model. Thus, all the synchronous generator reactive power capabilities have no influence on the voltage at steady state. This conclusion will have to be tested by the transient investigation to see whether it holds true for both steady state and transient conditions.

All transient investigations have been conducted with the AWF operating with a fixed active power of 15MW and fixed power factor of 0.95 leading (absorbing reactive power). This shall be known furthermore as PQ control.

5.2 Transient investigations

The steady state investigation determined the limits for PQ control; these were a limited active power output of 15 MW and the fixed power factor of 0.95 leading for the AWF. This PQ control is utilised by the transient investigation to test the voltage stability of the A1 Wind Farm under fault conditions.

Although a Western Power transient study was undertaken, the study utilised other simulation software. Therefore, the results of this transient investigation could not be validated due to large differences between the software and the outputs.

The transient investigation uses one worst case scenario to test voltage stability. However, unlike the steady state investigation, for the transient investigation the A1 Wind Farms power output and the zone substation load remains unchanged. The load is set to a peak of 40MW and A1 Wind Farms output set to peak of 15MW. Thus, the wind speed and load are assumed to be constant.

For voltage stability, peak load and peak wind farm generation is the worst case scenario. This is because at peak load the busbar demands the most reactive power and at peak generation the AWF is also absorbing the most reactive power. Therefore, a fault will cause the loads to absorb the most reactive power, while the AWF should have to generate a large amount of reactive power to support the voltage and maintain voltage stability.

To test voltage support and voltage stability, the worst case scenario will simulate a fault at 22kV busbar, this scenario is as followed:

Scenario 3 – peak load and generation conditions, 3 phase short circuit fault at 22kV busbar.

In the PowerFactory simulation, the short circuit fault is set to actuate at 0.5 seconds. The fault on the 22kV busbar will be cleared at 1.66seconds (1.16 after the fault has occurred) and total simulation time will run for 10 seconds, as this is a reasonable time for the voltage to achieve a new steady state.

The circuit breaker clearance times have been determined by section 2 of Western Power technical rules [2]. This stipulates for a voltage range of 66kV to 132kV, the circuit breaker (CB) must clear within 0.2 seconds and for a voltage range of 33kV and below the CB can take up to 1.16 seconds.

A fault on the 22kV busbar will be the best scenario to test the voltage control, network support capability and stability of the network. As this fault, will be depress the voltage for a longer period of time, due to the longer CB clearance time.

The Western Power technical rules [2] does not stipulate a critical time for voltage stability. However, the voltage must reach an acceptable steady state voltage level following the disturbance. This acceptable voltage level can be stipulated as 0.9 to 1.1 per unit of the nominal voltage within the nominated simulation time (10 seconds). Thus, if the voltage at the generator connection point or the 22kV busbar does not achieve 0.9 to 1.1 per unit (emergency conditions) within 10 seconds (assuming new steady state is achieved), then voltage instability has occurred and the generator will be disconnected.

5.3 Scenario 3, analysis using PQ control (22kV busbar fault)

For scenario 3, a fault has been simulated at the 22kV busbar under the above load and generation conditions. This simulation shows how the network behaves once the AWF has been isolated.

The simulation runs for a total of 10 seconds, the short circuit fault is actuated at 0.5 seconds into the simulation and cleared at 1.66 seconds. The fault current supplied by the A1 zone substation is 326 MVA, a value obtained from the Western Power database.

Figure 19 shows the results of the transient simulation at the point of connection of the AWF, known as the connection busbar.

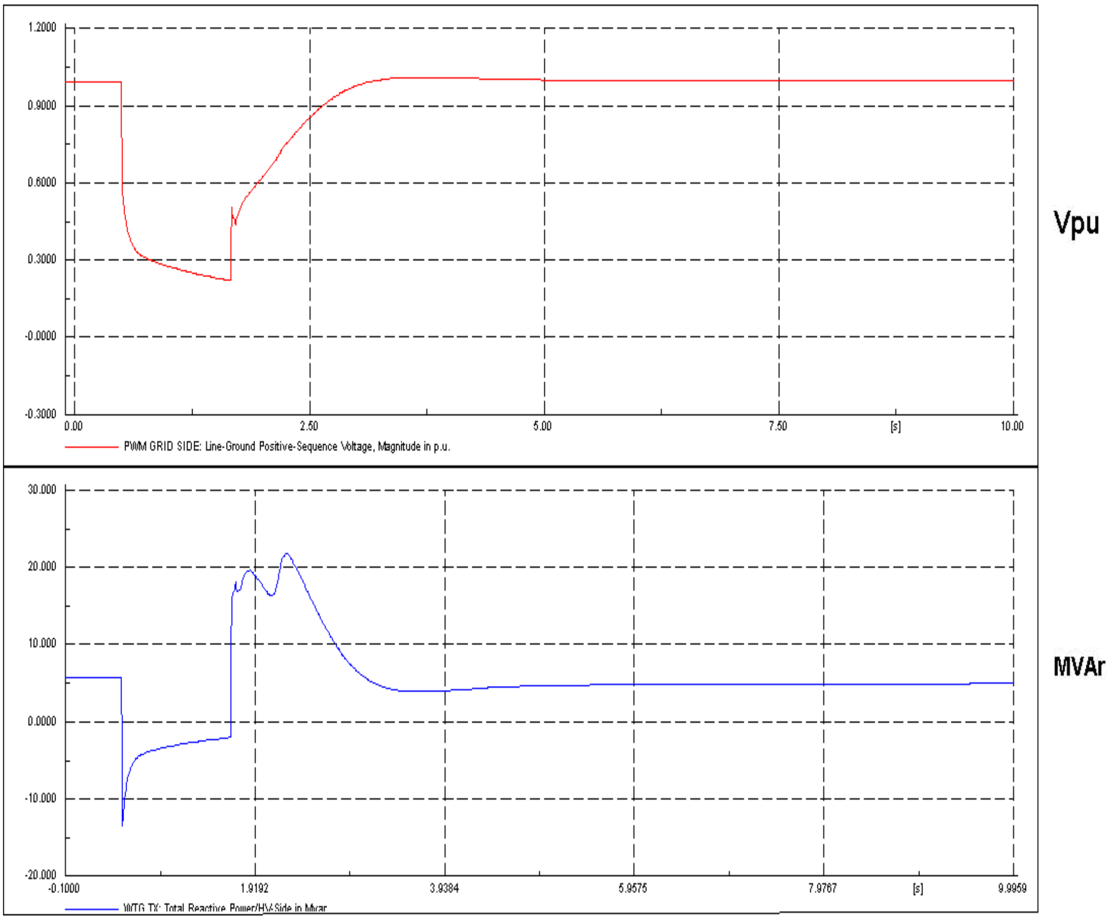

Figure 19: A1 Wind Farm connection busbar, 22kV busbar fault simulation

(Positive MVAr is absorbing from the grid and negative MVAr is generating to the grid)

5.3.1 Voltage per unit analysis

Figure 19 shows that before the fault occurs the voltage per unit is steady at 1.0 per unit and within normal operating limits. At 0.5 seconds into the simulation, the short circuit fault occurs at the 22 kV busbar. The voltage sags to 0.25 per unit during the fault and after 1.66 seconds the fault is cleared. At 2.7 seconds the voltage achieves an acceptable value of 0.9 per unit and at 3.1 seconds the voltage reaches 1.0 per unit. Therefore the system voltage is stable.

5.3.2 Reactive power analysis

Under constant PQ control Figure 19 shows that before the fault occurs 5.71 MVAr is absorbed by the AWF from the grid through the 20 MVA transformer. At 0.5 seconds into the simulation the short circuit fault occurs at the 22 kV busbar. After the fault occurs, the reactive power generated by the AWF increases up to 13MVAr. However, once the fault is cleared the AWF now reverts to PQ control and starts to absorb up to 21MVAr.

This shows that following the clearing of a fault, the AWF absorbs a large amount reactive power from the grid, although the voltage has not yet stabilised to acceptable limits. This is very undesirable for Western Power, as this would depress voltages even further and a large amount of reactive power would have to be fed from the A1 zone substation to the AWF (large voltage difference between sending and receiving).

However, while still absorbing the reactive power, the voltage at the connection point increases to 1.0 per unit. This should not occur following a fault situation. The AWF should revert to generating reactive power to help support the voltage to recover to 1.0 per unit.

This problem can be attributed to the constant PQ control. This is because PQ control makes the power converter absorb reactive power after the fault has been cleared when really the power converter control should be trying to control the voltage. The AWF should support the voltage by reversing the reactive power control from absorbing to generating, thus, the power converter should change from a leading to a lagging power factor.

At this point it would be ideal to test the transient behaviour of the negative load model. As it appears that the constant PQ control model is not ideal for transient analysis.

5.3.3 A1 Wind Farm model behaviour during transient analysis

The steady state investigation concluded that using a fixed PQ control for the “constructed” AWF model makes it behave like a negative load model. Therefore, unlike other wind turbine models (induction), all the synchronous generator reactive power capabilities (apart from its power limits) of the “constructed” model had no influence on the voltage at steady state.

It was also concluded that this negative load theory should also be tested under transient analysis.

For transient analysis, usually the voltage stability of the wind generator depends on the components of the rotating machinery [17]. These are as followed:

- Turbine aerodynamics
- Turbine mechanical controls, pitch and active stall
- Shaft dynamics
- Generator electric characteristics.

The AWF utilises the ENERCON design, thus, the generator is decoupled from the grid by the power converter. Therefore, the power converter controls the current output of the network side. Even during a fault, the current output from the power converter is not significantly higher than its rated output, this is because it is a current limited device and any additional generator over speeding can be minimized by the IGBT's blocking the current during fault conditions, and this current being dumped to a resistive load [17].

Two conclusions can be made from the above.

One is that the AWF does not significantly contribute to the fault current as its output is limited by the power converter.

Two, any change in the synchronous generator speeds will not be seen on the network side during transient analysis. This is because the output of the power converter can be controlled, regardless of the variations in the speed of the synchronous generator unit.

It could therefore be concluded that the usual rotating machinery components that affect voltage stability can be excluded for transient analysis of the AWF. Aditionally the “constructed” AWF can also be modelled as a negative PQ load for steady state and transient analysis.

However, from the conclusions of section 5.3.2, it apparent that constant PQ control of the “constructed” AWF model is not ideal for transient investigations. Using Figure 20, which compares the “constructed” AWF to the negative load model, it is apparent that because of this faulty control, the outputs (reactive power limits) of both models are drastically different.

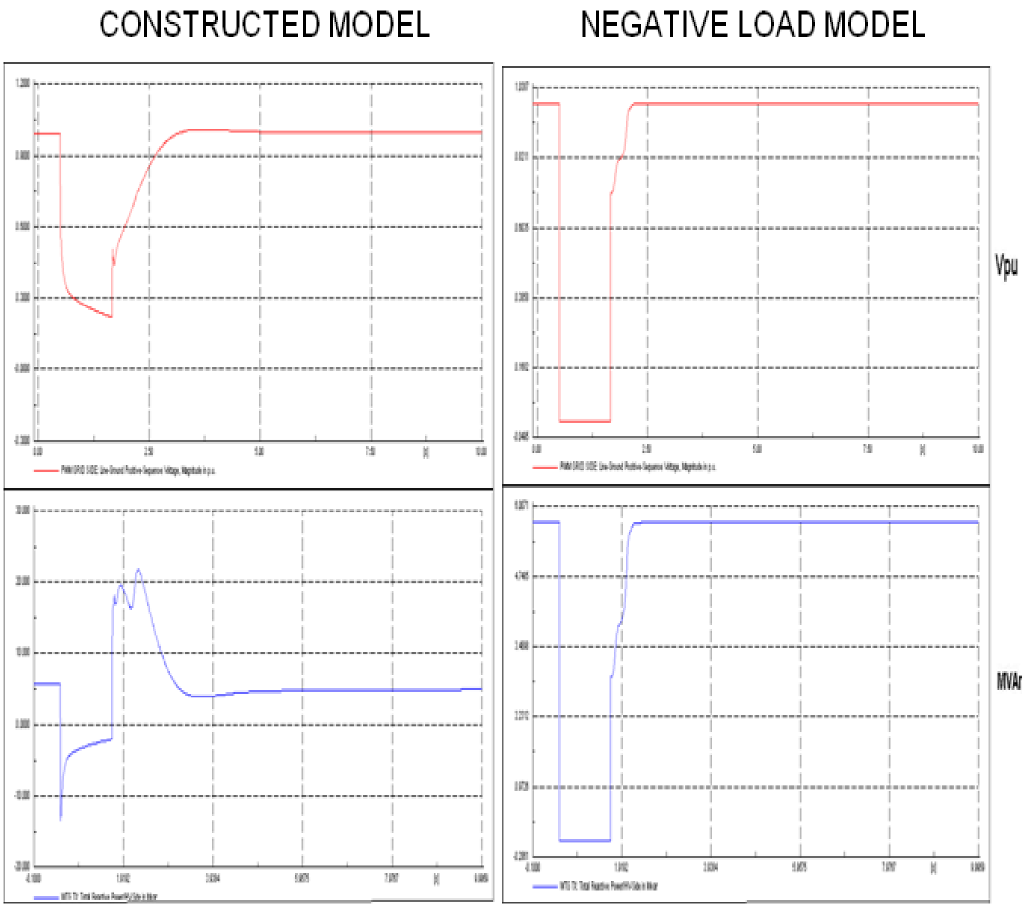

Figure 20: A1 Wind Farm connection busbar, 22kV busbar fault simulation.

(Positive MVAr is absorbing from the grid and negative MVAr is generating to the grid)

Therefore, the only thing that can be concluded is that while utilising constant PQ control, that these two models cannot be compared extensively to concur that the "constructed" AWF model behaves like a negative load under transient analysis.

From all the above, it can be concluded that the rest of the transient analysis will have to be completed using voltage control (voltage control) and the "constructed" AWF model.

5.4 Scenario 3, analysis using voltage control (22kV busbar fault)

To use voltage control, the pulse width modulator within the power converter was changed from a constant PQ control of 15MW and -4.93MVAr (0.95 leading) to constant voltage control, using an AC voltage set point of 1.0 per unit. This means that once the fault has been cleared the power converter will change its control to generate reactive power. This will ensure that voltage achieves a steady state of 1.0 per unit as quickly as possible.

Once again, the fault has been simulated at the 22kV busbar under the peak load and generation conditions. The simulation runs for a total of 10 seconds, the short circuit fault is actuated at 0.5 seconds into the simulation and cleared at 1.66 seconds. Figure 21 shows the results of the transient simulation at the connection point of the AWF.

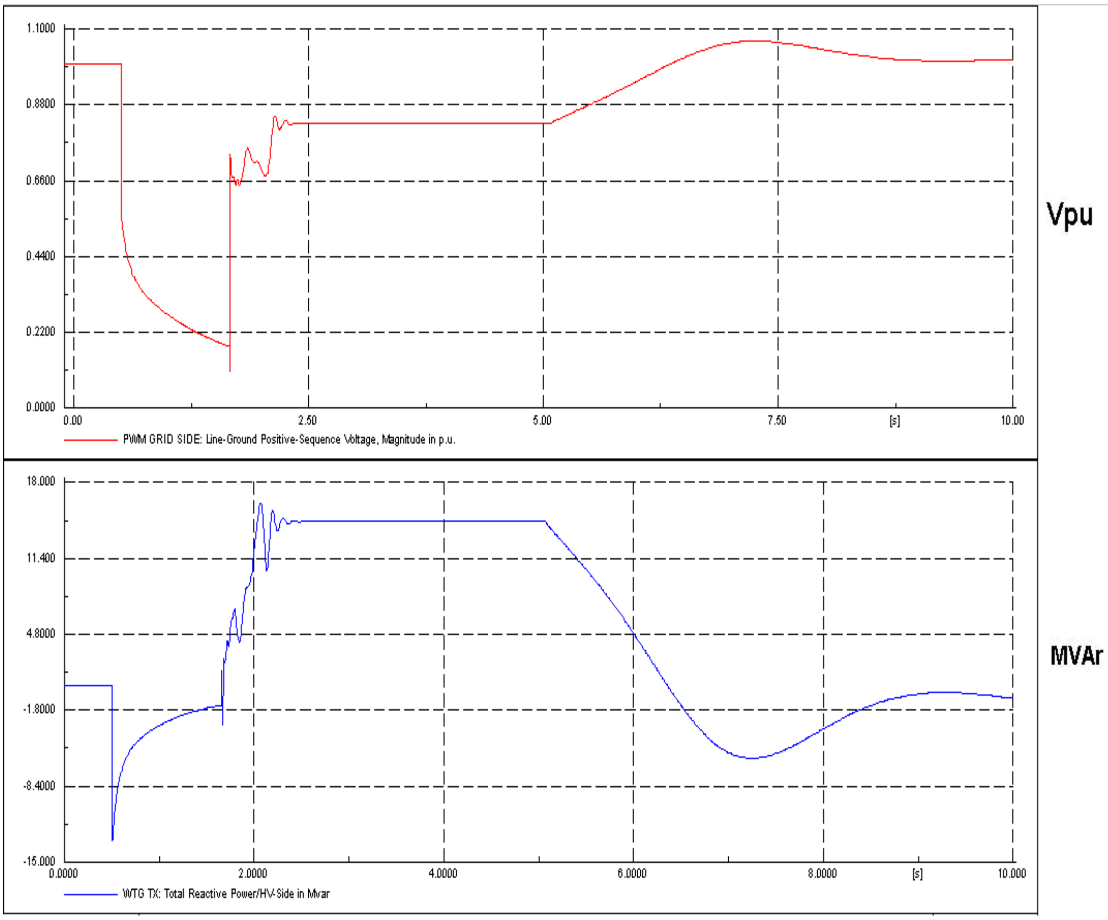

Figure 21: A1 Wind Farm connection busbar, 22kV busbar fault simulation (voltage control)

(Positive MVAr is absorbing from the grid and negative MVAr is generating to the grid)

5.4.1 Voltage per unit and reactive power analysis (voltage control)

Figure 21 shows that before the fault occurs the voltage per unit is steady at 1.0 per unit. At 0.5 seconds into the simulation the short circuit fault occurs at the 22 kV busbar. The voltage per unit sags to 0.1 during the fault and after 1.66 seconds the fault is cleared. At 2.5 seconds the voltage achieves a value of 0.8 per unit. This new steady state value is outside the voltage limits of 0.9 per unit, therefore the voltage is unstable at this point. This instability can be attributed to the large amount of reactive power being absorbed by the AWF after the fault has been cleared.

At 5 seconds into the simulation the controller has determined that the AC voltage set point of 1.0 per unit will not be achieved unless the power converter changes the AWF from absorbing to generating reactive power. It reality, this would occur faster than this, this is because the control algorithm within PowerFactory is slower than the actual ENERCON controllers. This can be seen in Figure 21, at this point the controller reverts the wind farm from absorbing to generating reactive power (positive is absorbing from the grid and negative is generating to the grid) and the result is that the voltage now increases to its AC voltage set point of 1.0 per unit. Once the AC voltage over shoots the set point the reactive power generated by the AWF reduces to the pre fault value and the voltage becomes steady at 1.0 per unit.

Unlike PQ control, Figure 21 shows that using voltage control for transient analysis produces realistic results. As the wind farm reverts to generating reactive power once the voltage set point has not been reached. This change can be attributed to the under voltage ride through capabilities of the A1 Wind Farm. If these capabilities had not existed then the AWF would have been disconnected once the voltage became unstable. Therefore, if the AWF had been disconnected rather than generating reactive power, the voltage would not have recovered as quick and may have resulted in additional load shedding or reactive power support from the 132kV feeders.

From the steady state analysis, it was concluded that a constant PQ control of 15MW and -4.93 MVAr results in the least impact on the 22kV busbar of the A1 zone substation. However, using the same PQ control for transient analysis caused problematic results. Therefore, the AWF had to utilise voltage control under transient conditions.

Voltage control should be triggered by the under voltage of 0.8 per unit, (shown in Figure 21) as discussed in section 3.7.5, the AWF under voltage ride through.

5.4.2 Conclusions from the transient investigation (voltage control)

From the transient analysis, it can be concluded, that it is important for the AWF to have under voltage ride through capabilities. This is important to the voltage control and stability of the A1 network, because this specific capability allows the AWF to remain online and to generate reactive power output even if its voltage is under the required limits.

The studies conducted under PQ control indicate that immediately after clearing the fault the wind farm is absorbing reactive power. In turn, this would lead to a depression of the network voltage. Therefore, under PQ control, if the wind farm disconnected after the fault, then the voltage recovery would be quicker.

However, clause 3.3.3.3 (f) of the technical rules [2] does not allow generators to absorb reactive power during voltage recovery. Therefore, there is an issue with the PQ control for voltage recovery under transient conditions.

This issue is overcome by the utilisation of voltage control for the AWF. Under voltage control, the model responds by generating power after fault clearance and the network voltage is supported and voltage instability averted. Therefore, under voltage control, if the wind farm disconnected after the fault, then the voltage recovery would be slower.

It can be concluded that by reverting to voltage control from constant PQ control, the AWF has also reverted from absorbing reactive power to generating reactive power. In doing this the AWF has provided reactive power support following the fault condition.

Within the transient investigation, at first, transient voltage instability occurred, as the voltage did achieve an acceptable steady state voltage following the transient event. However, long term steady state voltage instability was avoided due to the under voltage ride through capabilities of the AWF. This is because that once the under voltage ride through capabilities (through voltage control) were actuated by the under voltage set point, the voltage per unit achieved a new acceptable steady state voltage within the simulation timeframe.

Therefore, it is now obvious why fault ride through capabilities are required by [2] for Western Power networks utilising wind energy generation. That the under voltage ride through capabilities of the AWF can contribute to the voltage control, network support capability and stability of the A1 distribution network.

6 Scope for future work

There are a number of additional investigations that could be performed using this thesis as a research basis.

6.1 Expansion of the A1 Wind Farm (AWF)

Currently the owner of the A1 Wind Farm is planning to increase the number of wind turbines to 18. However, as the original wind turbine is no longer manufactured by ENERCON, a turbine of a greater capacity will be installed. This new wind farm may require additional static reactive power compensation (STATCOM) and more complex control between the wind farm and the STATCOM. Within this investigation the optimum size of the wind turbines and STATCOM could be determined and transiently tested.

6.2 Optimising the active power output

Future research could investigate the affect of changing the active power limit above 15 MW. This would produce different steady state and transient results. This way the maximum output could be optimised and the research could investigate the AWF under current generating conditions, rather than its initial commissioning conditions and limitations.

6.3 Further investigation of voltage instability

Voltage instability could be further investigated by reducing the fault level of the external source and increasing the motor load within the PowerFactory simulation. This would occur if one of the transmission feeders was isolated for maintenance or a 132kV fault. The size of the motor load and fault level could be determined to investigate at what load and fault level that voltage instability would occur. When it does occur, the motor speed and torque could be viewed and analysed to determine if the motors stall and what additional affect this would have on the voltage stability.

7 Conclusion

The purpose of this thesis was to investigate the voltage control, network support capability and stability of the A1 distribution network and AWF under steady state and transient conditions. This thesis was completed using research, simulation modelling and steady state and transient analysis of the A1 Wind Farm (AWF).

The research outlined that when using the ENERCON concept, coupling the grid side of the synchronous generator to the power converter allows the wind turbine to have full control of its reactive power and power factor. The power converter allows the AWF to participate in maintaining the voltage control and support through reactive power generation and voltage stability using the Under Voltage Ride Through capabilities.

The power converter can be controlled using fixed and limited PQ control for steady state analysis. However, it should be noted, that the same PQ control proved problematic for the transient analysis. After a fault occurred, the A1 Wind Farm did not generate reactive power as it should to support the voltage.

Therefore, it was concluded that PQ control was not appropriate for transient network conditions and the power converter should revert to voltage control to generate reactive power. In reality this is carried out, as the technical rules [2] stipulate that a generator is not permitted to absorb reactive power during voltage recovery.

For the steady state investigation, it was concluded that operating the AWF at a limited active power output of 15MW and a power factor of 0.95 leading (absorbing reactive power) resulted in the least impact on the voltage of the Western Power customers. When using fixed PQ control for the "constructed" AWF, the model acts like a negative load model. Thus, all the synchronous generator reactive power capabilities had no influence on the voltage at steady state.

For the transient investigation, it was concluded that it is required for the A1 Wind Farm to have under voltage ride through (UVRT) capabilities. UVRT capabilities are important to the voltage control, support and stability of the A1 network, because this specific capability allows the AWF to remain online and to generate reactive power even if its voltage is under the required limits and voltage instability has already occurred.

The implications of these conclusions are that, the wind energy generation must be limited during commissioning to limit the impact on voltage fluctuations. The power converter used for the ENERCON wind turbines, is required for voltage control, network support capability and stability of the A1 distribution network.

8 References

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Appendices

Appendix A – Data Sheets and PowerFactory model parameters

1. 240mm², 22kV, termitex, underground copper cables (termitex protects against termites).

- K2 -
ELECTRICITY CORPORATION

SCHEDULE K2

UNDERGROUND CABLE DATA SHEET

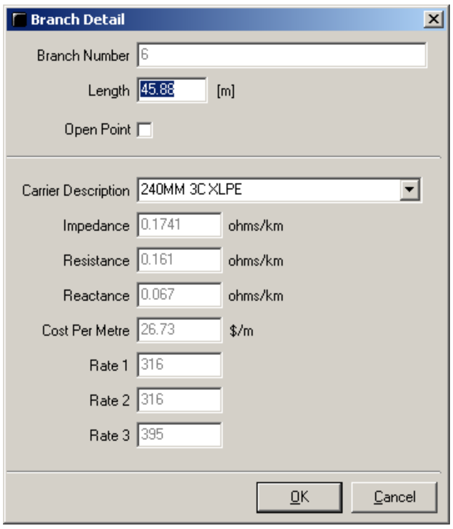
ITEM NO:	1.2		STOCK NO:	EE2164	
VOLTAGE:	12.7/22	kV	COMPLIES WITH STANDARD NO:	AS1429	
STOCK DESCRIPTION:					
	3 X 1 240MM² CCU XLPE HD/WST/PVC/HDPE with Termitex				
DETAILED DESCRIPTION:					
Sheath thickness - one layer	n/a	mm	Sheath thickness - inner PVC	1.3	mm
CU Screen Coverage (>40%)	47.7	%	Sheath thickness - outer HDPE	2	mm
Pulling Tension (Max Sock) Per Core	2243	kg.	CU Screen CS Area	70	mm²
Minimum Bending Radius					
Installed - Bundle	1480	mm	Core Insulation Dia.	31.04	mm
One cable	675	mm			
Installing - Bundle	2465	mm	Overall Cable Dia.*	44/95	mm
- One cable	1125	mm			
Mass:	11.6	kg/m	Semi-conductive Insulation Screen Diameter	32.7	mm
CURRENT RATINGS			ZERO SEQ. Z (Incl. Metallic screen)		
At Air Temp 40° C			At 20C	0.354 +j0.055	ohms/km
Ground Temp 25°C Soil Resitivity 1.2°C m/W Depth of laying = 800mm Solid Bonded			At Rated Temp	0.45 +j0.055	ohms/km
			POS.SEQ.Z		
Unenclosed:	574	A	At 20C	0.077 +j0.144	ohms/km
Direct Buried:	479	A	At Rated Temp	0.098 +j0.114	ohms/km
Underground Ducts: INT. 125MM EXT. 133MM	422	A	SHUNT CAPACITANCE	0.302	µF/km
FAULT RATING	10.4	kA	for 1 sec single phase to earth fault		
	34	kA	for 1 sec 3ph symmetrical fault		
VOLTAGE DROP	0.261	mV/A/m	@ 90° C		
CORE IDENTIFICATION:	PRINTED PHASE NUMBERS ON CORES AND SHEATH				

REMARKS:

* For 3 x 1c twisted cables, also state overall diameter of 1 core e.g.40/87mm

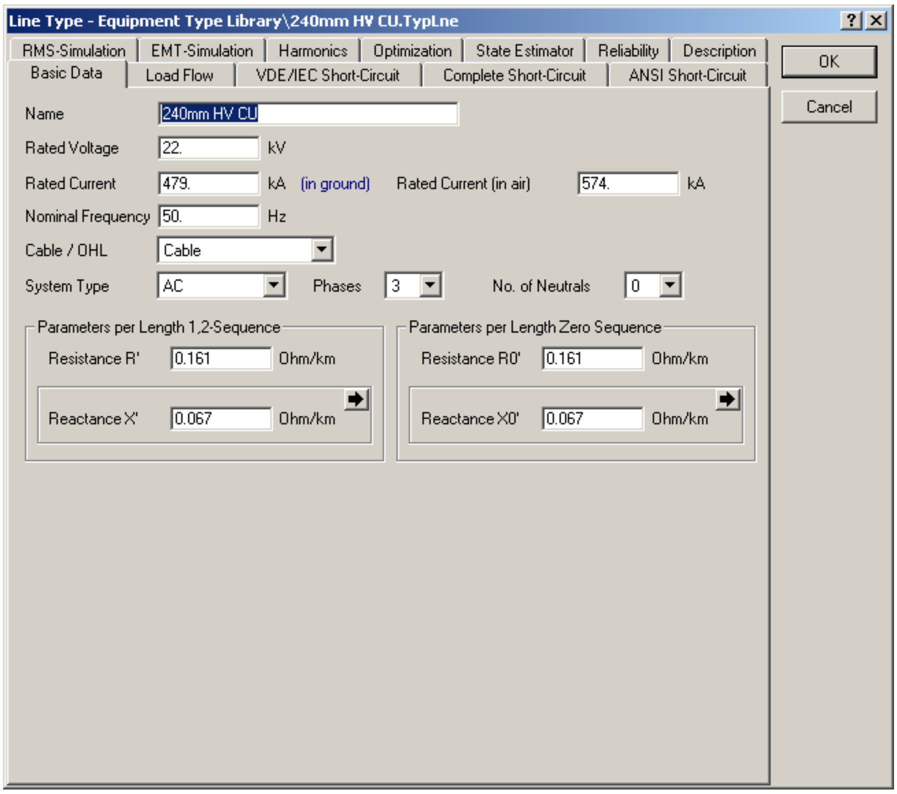
Tender Number:		Vendors Signature:	
Vendor's Name	PRYSMIAN CABLES	Date:	/ /

Used in PFY model due to losses

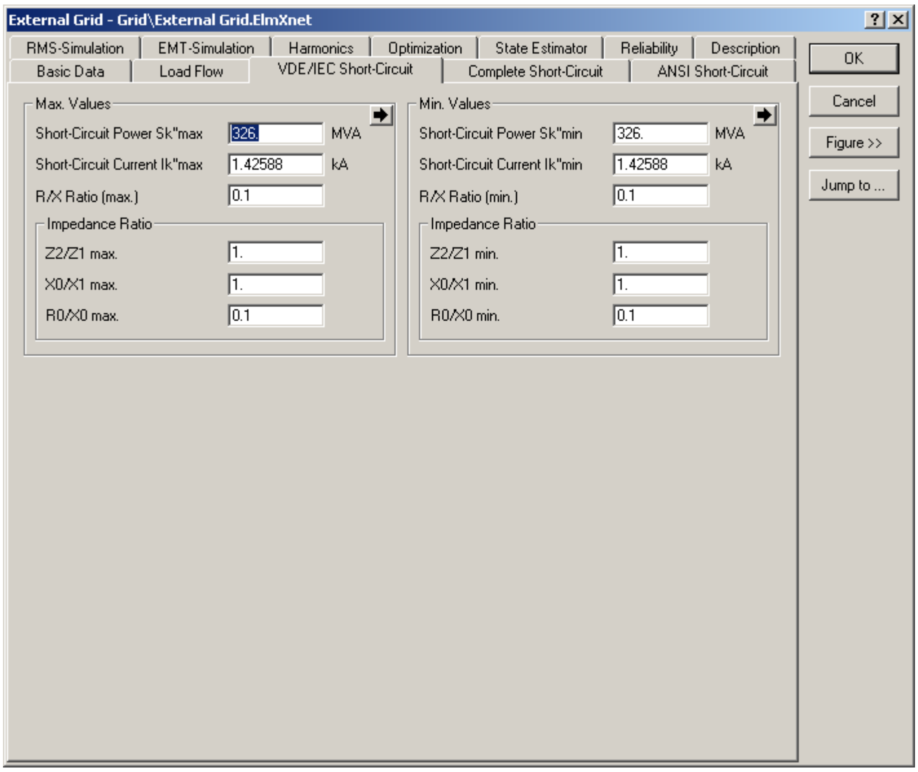


Model Parameter used in Powerfactory

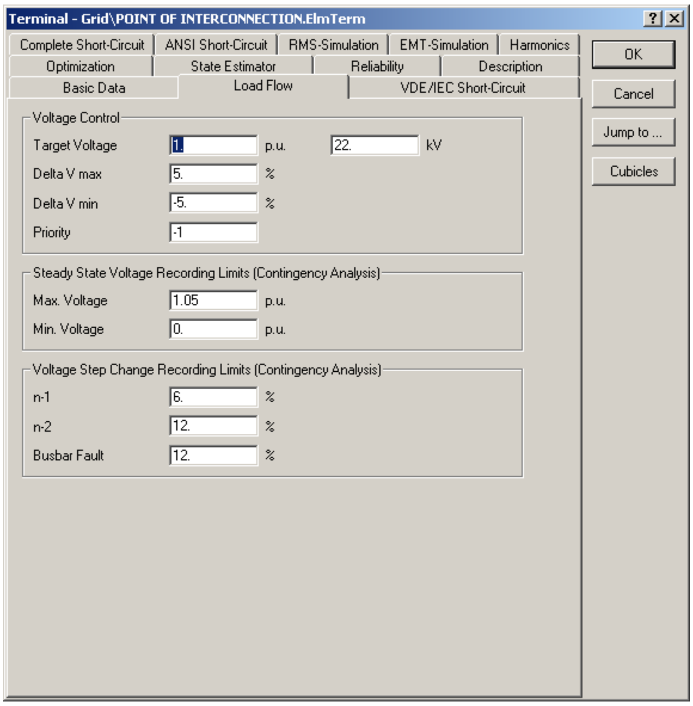
2. Line Type (cable)



3. External Grid model

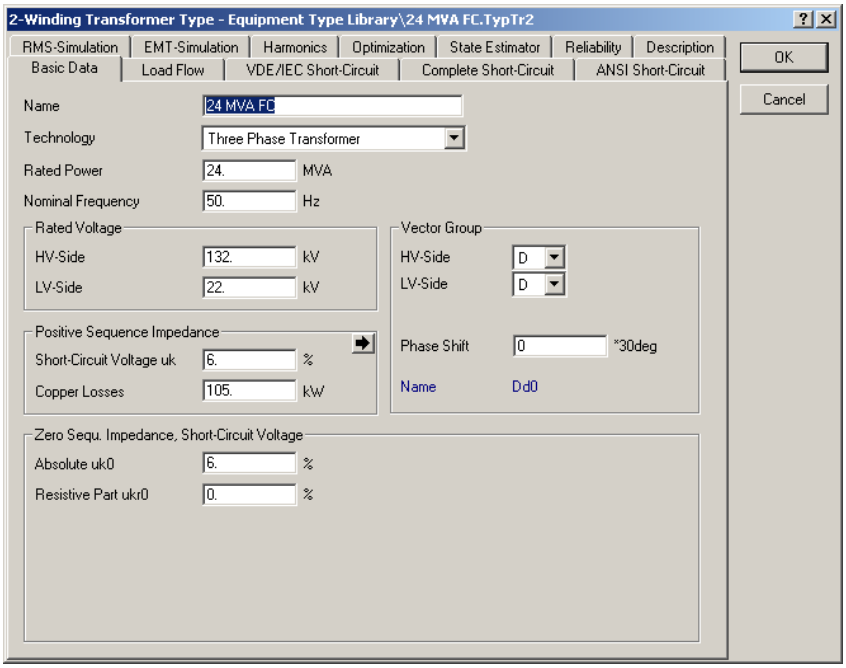


4. Terminal model

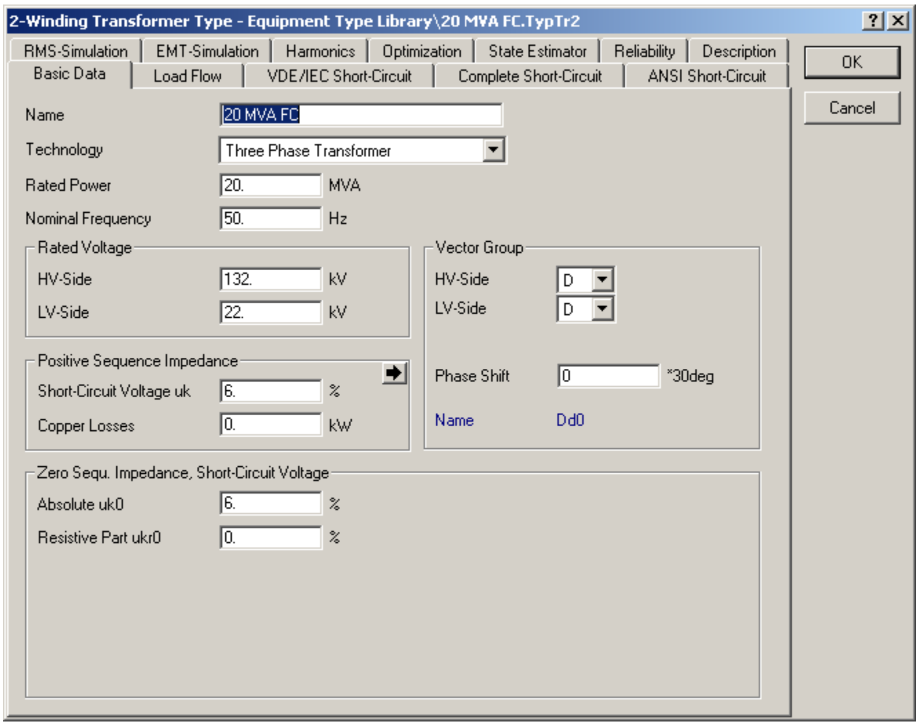


5. Transformer model

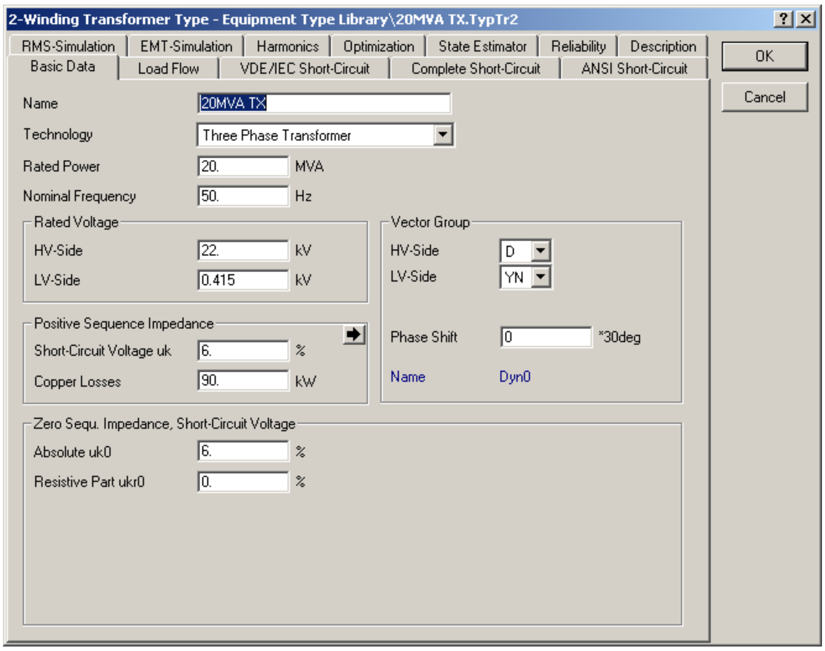
A1 Zone Substation Transformer



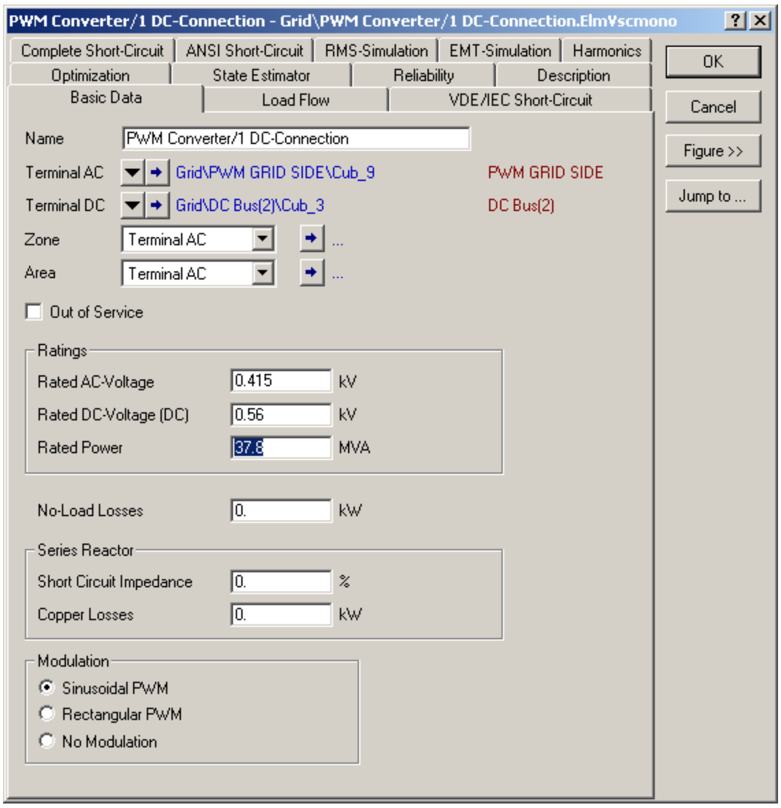
A2 and A3 Zone Substation Transformer



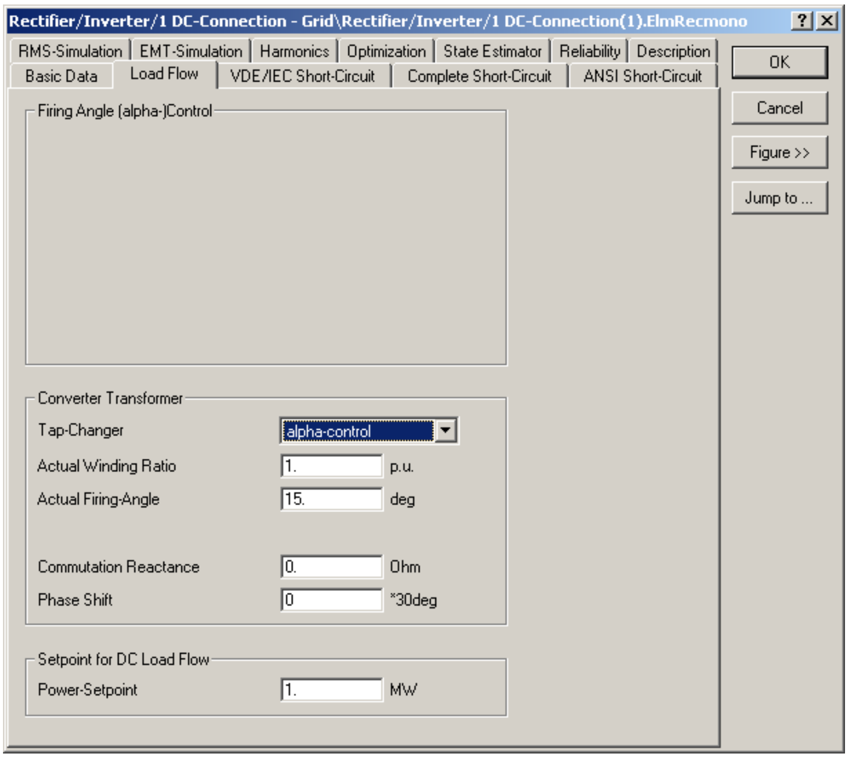
A1 Wind Farm Transformer (WTG TX)



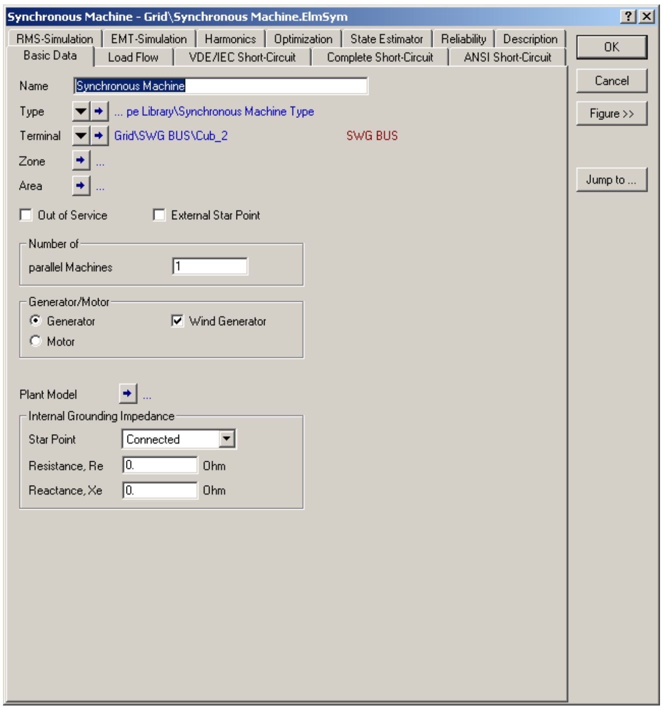
6. Pulse Width Modulation Inverter

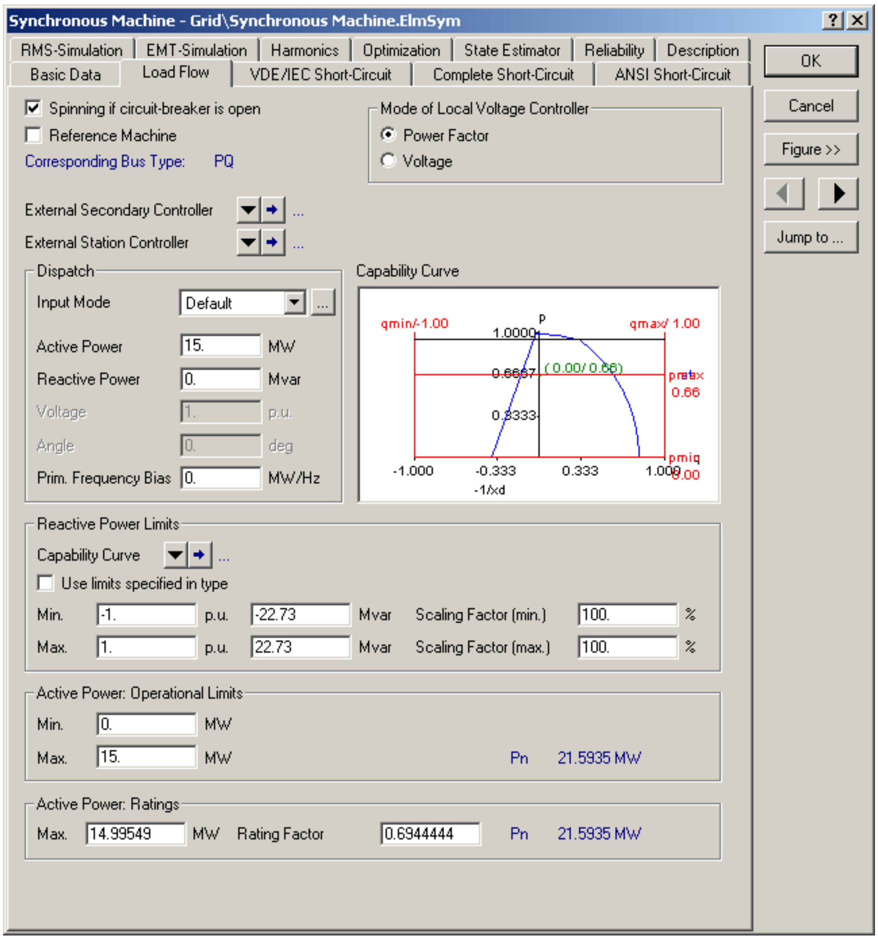


7. Rectifier

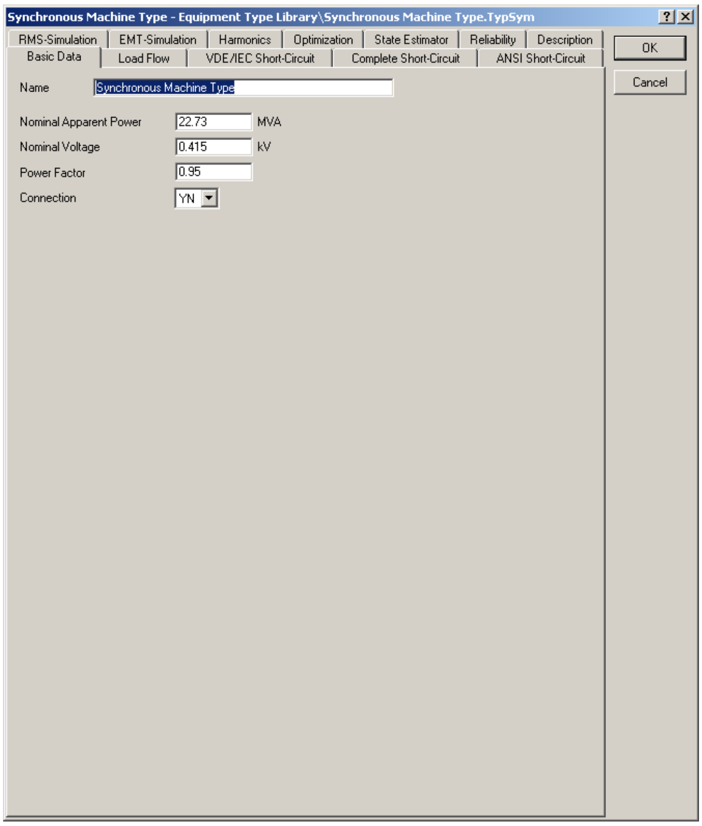


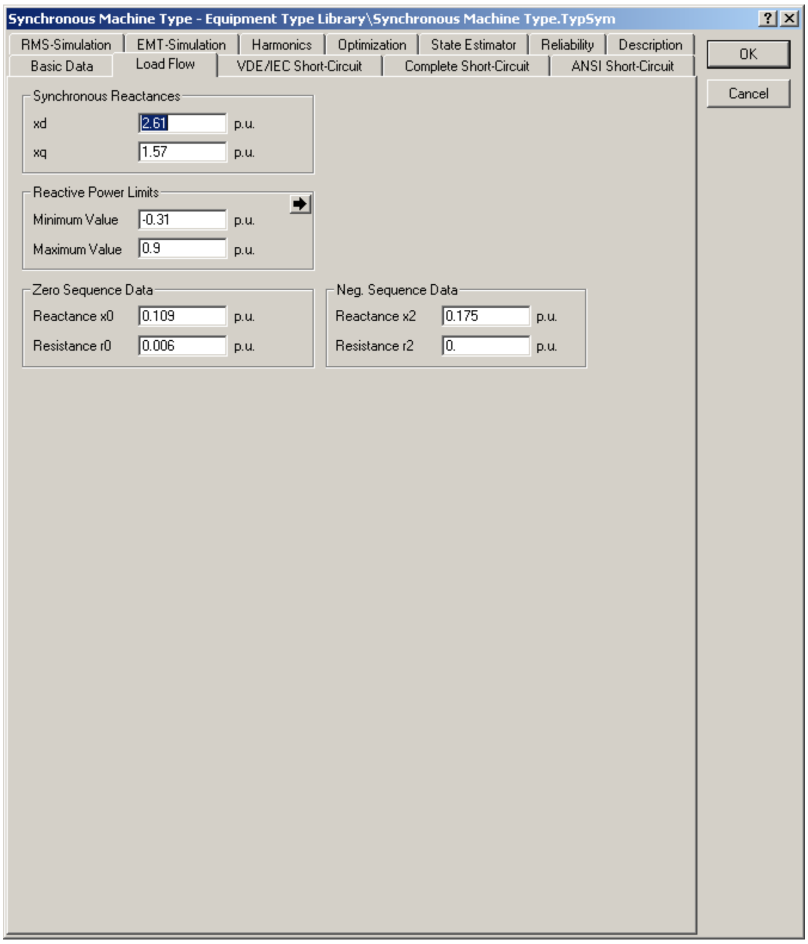
8. Synchronous Generator




Synchronous Machine - Grid\Synchronous Machine.ElmSym
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
Complete Short-Circuit
ANSI Short-Circuit
OK
Cancel
Figure >>
Jump to ...
Spinning if circuit-breaker is open
Reference Machine
Corresponding Bus Type: PQ
Mode of Local Voltage Controller
Power Factor
Voltage
External Secondary Controller
External Station Controller
Dispatch
Input Mode Default
Active Power 15. MW
Reactive Power 0. Mvar
Voltage 1. p.u.
Angle 0. deg
Prim. Frequency Bias 0. MW/Hz
Capability Curve
qmin/-1.00
qmax/ 1.00
(0.00/0.66)
pmax 0.66
pmin 0.00
-1/xd
Reactive Power Limits
Capability Curve
Use limits specified in type
Min. -1. p.u. -22.73 Mvar Scaling Factor (min.) 100. %
Max. 1. p.u. 22.73 Mvar Scaling Factor (max.) 100. %
Active Power: Operational Limits
Min. 0. MW
Max. 15. MW Pn 21.5935 MW
Active Power: Ratings
Max. 14.99549 MW Rating Factor 0.6944444 Pn 21.5935 MW

Type


Synchronous Machine Type - Equipment Type Library\Synchronous Machine Type.TypSym
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
Complete Short-Circuit
ANSI Short-Circuit
OK
Cancel
Name Synchronous Machine Type
Nominal Apparent Power 22.73 MVA
Nominal Voltage 0.415 kV
Power Factor 0.95
Connection YN


Synchronous Machine Type - Equipment Type Library\Synchronous Machine Type.TypSym
RMS-Simulation
EMT-Simulation
Harmonics
Optimization
State Estimator
Reliability
Description
Basic Data
Load Flow
VDE/IEC Short-Circuit
Complete Short-Circuit
ANSI Short-Circuit
OK
Cancel
Synchronous Reactances
xd 2.61 p.u.
xq 1.57 p.u.
Reactive Power Limits
Minimum Value -0.31 p.u.
Maximum Value 0.9 p.u.
Zero Sequence Data
Reactance x0 0.109 p.u.
Resistance r0 0.006 p.u.
Neg. Sequence Data
Reactance x2 0.175 p.u.
Resistance r2 0. p.u.

Appendix B – PowerFactory A1 Wind Farm Model

Appendix B is located in the folder named “Appendices” in the root directory of the enclosed compact disc. It consists of a PowerFactory export file (.PFD) that can be imported into PowerFactory Version 14 only.

Import this file into PowerFactory using

File- Import - Data (.PFD) – Select A1 Wind Farm – Execute

Then click file – activate project – A1 Wind Farm

For help with steady state and transient investigations, email Brendan Fidock on

Email: brendan.fidock@westernpower.com.au

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